New Energy

India

Sector View: **Neutral** NIFTY-50**: 19,512** **October 09, 2023**

Green Hydrogen: Hope + Hype

It is an undeniable fact that our planet is getting warmer. In order for it to stay habitable, GHG emissions must be drastically reduced. Although renewables have enormous potential and will never exhaust, they lack the flexibility of fossil fuels, making the transition a difficult one. In this primer, we discuss how the versatility of Hydrogen (H_2) brings us great promise and hope. Green hydrogen (GH) can make the energy transition faster and smoother. As costs fall, it may be competitive with H_2 from fossil sources, but we acknowledge the hype around it currently. H_2 is difficult to handle; it would also require incentives/carbon taxes, along with mandatory usage obligations. GH would likely initially find usage in refining/fertilizers, but will be more inefficient than BEVs for mass transport.

Versatility of H_2 makes it a fuel of great hope for energy transition

To limit global warming, greenhouse gas (GHG) emissions need to be reduced urgently. End-use must be electrified wherever possible and energy generation must be decarbonized. Although renewables have made considerable progress, they have limitations. Solar/wind power is available for few hours in a day. Electricity storage and long-distance transmission are difficult. In hard-to-abate sectors, renewables cannot replace fossil fuels.

H_2 is a remarkably versatile molecule. GH produced using renewables has no emission at all. It can be used in combustion engines just as fossil fuels or as an energy carrier. Using fuel cells, it can generate electricity. It can create synthetic fuels such as ammonia/jet fuel. GH can act as a connector and integrate renewables in energy systems. In the net-zero scenario by 2050, even as electricity will meet ~70% of the end-demand, H_2 can account for 15-20% of final energy demand.

Even at US$1-2/kg, GH will need support; FCEVs may not compete with BEVs

With countries and corporates racing to reach net-zero as soon as possible, GH is getting a lot of attention. GH production is currently expensive and requires financial incentives/carbon tax on fossil fuels to spur adoption in hard-to-abate sectors. The target is to reduce GH costs by 80-85% over this decade to just US$1/kg. This will make GH cheaper versus grey/blue H_2 and other fossil fuels. Initially, as the switch to GH needs fresh capex (and makes existing grey H_2 investments redundant), the industry will need to be pushed by mandatory GH consumption obligations. Much less efficiency and difficulty in handling make GH inferior to battery EVs (BEVs) used for mass transport.

India joins hydrogen bandwagon with National Green Hydrogen Mission

In 2021, the Indian government initially announced the National Green Hydrogen Mission (NGHM, notified in January 2023). With the government announcing several incentives, there has been a rush to announce H_2 plans by corporates. Niti Aayog had estimated a 4X rise in H_2 consumption by 2050. NGHM targets are more aggressive, with aspirations to make India a global H_2 hub.

Several corporates have announced plans; too early to see any benefit

Starting with Reliance in 2021, several corporates have joined the GH bandwagon and announced plans. In our view, so far, the actual progress is slow. However, this will be an emerging area of investment, which we will keenly watch.

Full sector coverage on KINSITE

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Executive Summary

Energy transition is a must, but renewables have limitations

To limit the global warming to 1.5°C above pre-industrial levels, there is a growing consensus on reducing GHG emission (CO_2 in particular) and reaching net-zero carbon emissions as soon as possible. The path to net-zero emissions will have a multi-pronged strategy to achieve emission reductions across a wide spectrum of sectors. Although renewable sources such as solar/wind have made considerable progress, they have their limitations. Solar/wind power is available for a few hours in a day. Electricity storage and transmission over a long distance is also a challenge. Furthermore, in hard-to-abate sectors, renewables cannot replace fossil fuels. There is a need to deploy new and emerging clean-energy technologies.

H_2 is a fuel of great hope for integrating renewable to energy systems

H_2 is the simplest and lightest molecule, with one of the highest energies per kilogram compared with conventional fuels (3X of gasoline, 3.3X of diesel). It is also a remarkably versatile molecule. GH produced from renewable energy (wind or solar) through electrolysis has zero emissions and has several potential use cases. GH can be used in combustion engines just as fossil fuels or as an energy carrier. It can generate electricity and synthetic fuels such as ammonia/jet fuel. It can act as a connector and integrate renewables in energy systems, and is a fuel of great hope.

According to industry estimates, by 2050 even as electricity will meet ~70% of the end-demand, H_2 can account for 15-20% of the final energy demand.

GH cost will decline sharply; yet it will need incentives and may not compete with BEVs

Currently, the cost of GH (~US$4.5-6/kg) is expensive compared with gray and blue H_2. In order to spur GH adoption in hard-to-abate sectors, there will be a need for financial incentives for GH and/or carbon tax on fossils. However, in the longer run, the cost of GH is likely to decline sharply. The key drivers for cost reduction will be the decline in renewable power and electrolyzer costs. The US Department of Energy (DoE) has set a target to reduce GH costs to US$1 per 1kg in a decade (1-1-1). This will make GH cheaper versus grey/blue H_2, and also other fossil fuels, further increasing its adoption.

Despite the likely cost declines for GH, replacing conventional fossil fuels by H_2 (or its derivatives) will entail higher costs. For example, the cost of synthetic ammonia produced using US$1/kg H_2 will still be ~55% higher versus alternate (VLSFO). To bring parity, there may still be a need for support such as green incentive or carbon taxation for industries to switch to GH. GH is likely to find uptake initially in the refining and fertilizer sectors and can become competitive over the longer term in other sectors such as steel, shipping and aviation. However, much lower efficiency (~40%) and difficulty in handling make GH inferior to battery EVs (BEVs) used for mass transport.

India aspiring to be GH hub

Indian government is committed to a low-carbon development strategy and is targeting a sharp reduction in emission intensity. India's Panchamrit or five-nectar strategy, includes 1) 500 GW of non-fossil energy by 2030, 2) 50% energy requirement from renewables by 2030, 3) reduction in projected carbon emissions by 1 bn tons by 2030, 4) reduce the carbon intensity of economy by 45% before 2030 over 2005 levels and 5) target of net-zero emissions by 2070. In addition, it is targeting to become energy independent by 2047.

India already has one of the lowest renewable energy prices in the world. Furthermore, the Government of India's target of scaling up non-fossil energy capacity to 500 GW by 2030 would likely enable sufficient renewable energy generation for scaling up GH production in India. With the National Green Hydrogen Mission (NGHM), India is aspiring to be a H_2 hub.

Furthermore, the Government of India's target of scaling up non-fossil energy capacity to 500 GW by 2030 would likely enable sufficient renewable energy generation for scaling up GH production in India.

India's current GH consumption is about 6 mmtpa annually. Bulk of it is produced from fossil fuels (mainly natural gas), and consumed in-house. Niti Aayog had estimated that India's H_2 demand would increase over 4X by 2050. The share of GH from being NIL currently would increase to nearly 100%. NGHM targets are even more aggressive.

To encourage the early adoption of GH, the government has announced a Rs197 bn outlay for setting up electrolyzer manufacturing and GH production. Mandatory GH consumption obligations for hard-to-abate sectors such as refining and fertilizers can spur early consumption of GH in India.

Corporates have joined GH bandwagon; near-term benefit low, but positive for LT

Transition to GH will be capex-intensive, without any significant advantage initially as compared with the current gray H_2 usage. On our estimate, ~US$18-22 bn of capex would be required to switch one-third of India's H_2 requirement in refining to green. We believe industries would need to be pushed to switch to GH initially, through mandatory GH obligations, fiscal initiatives and/or carbon taxes. However, as GH costs decline, we expect the switch to GH to accelerate. Furthermore, as the GH costs decline, the usage could diversify into other segments in India such as steel production, heavy-duty vehicles and even transport.

With a rising focus on net zero, several Indian corporates have also announced their own net-zero targets. We note several corporates such as RIL, Adani New Industries Limited (ANIL) and several public sector units (PSUs) have announced ambitious plans for GH. However, these are still at the pilot stage and progress is slow. We believe as GH becomes more competitive and the government imposes GHCO mandates and provides fiscal incentives, there will be a pick-up in activity.

1

Why hydrogen?

To limit the global warming to 1.5°C above pre-industrial levels, there is growing consensus on reducing GHG emissions and reaching net-zero as soon as possible. Although renewables have made considerable progress, they have limitations. Due to its versatility, the hydrogen molecule can tackle a lot of these challenges; in our view, it is a fuel of great hope. GH production has no emissions. It can be used in combustion engines just as fossil fuels or as an energy carrier. It can generate electricity and synthetic fuels such as ammonia/jet fuel. It can act as a connector and integrate renewables in energy systems. According to industry estimates, by 2050, even as electricity will meet ~70% of the end-demand, H_2 can account for 15-20% of the final energy demand.

Decarbonization—a must for planet to remain habitable

With increasing emissions our planet is heating up

With higher human interventions over the past two centuries, our planet has been warming up steadily. Compared with the mid-20th century, global average temperatures have increased nearly 0.9 Degree Celsius (Exhibit 2). From pre-industrial levels (late-1800s), the earth is already warmer by about 1.1°C. There is a widespread consensus in the scientific community that if the planet warms more than 1.5°C, increased temperatures could cause irreversible damage. It could potentially make parts of the world uninhabitable.

The emission of three GHGs—carbon dioxide (CO_2), methane and nitrous oxides—is the key contributor to rising temperature levels and climate change. Among these GHGs, CO_2 is the biggest contributor to climate change.

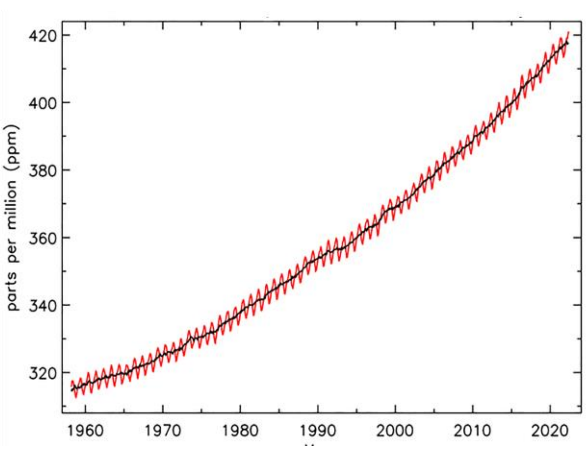
- **Burning fossil fuels is the main driver of rising CO_2 concentrations in the atmosphere. Global CO_2 emissions have increased to ~37-38 bn tons annually from about 11 bn tons per year in the 1960s.** In 2022, the **global average CO_2 concentration in the atmosphere rose more than 2.1 parts per million (ppm) to 417 ppm**. Atmospheric CO_2 is now 50% higher than pre-industrial levels. Importantly, 2022 was the **11th consecutive year** of CO_2 concentration rising more than 2 ppm. It is to be noted that three or more consecutive years of 2 ppm growth were never reported before 2013.

- **Atmospheric methane concentrations have also been increasing** and rose 14 parts per billion (ppb) to 1,912 ppb in 2022. Though the concentration level of methane is lower (versus CO_2), it is much more potent at trapping heat.

- **Nitrous oxide levels have also been rising**. In 2022, nitrous oxide levels increased 1.2 ppb to 336 ppb. Compared with pre-industrial levels, the increase is about 25%. The key reasons for rising nitrous oxides are the increasing use of nitrogen fertilizers and manure generated in agriculture.

Atmospheric CO_2 has increased over 2 ppm for 11 years now

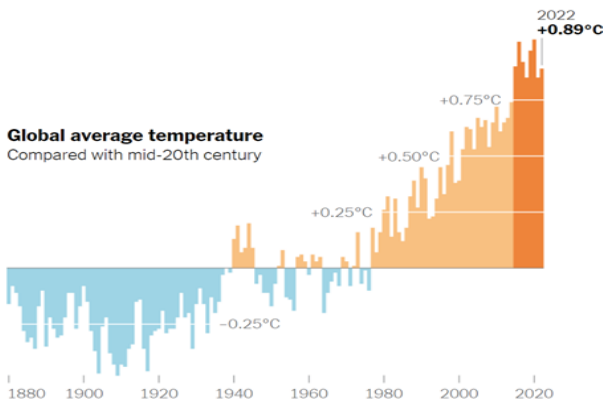
Exhibit 1: Atmospheric CO_2 at Mauna Loa Observatory (ppm)



Source: NOAA Global Monitoring Laboratory, US; Kotak Institutional Equities

Global average temperature has increased 0.9°C from mid-20th century and 1.1°C from late-1800s.

Exhibit 2: Global average temperature (versus mid-20th century)



Source: NASA Goddard Institute of Space Studies; Kotak Institutional Equities

Net-zero seems must for planet to remain habitable

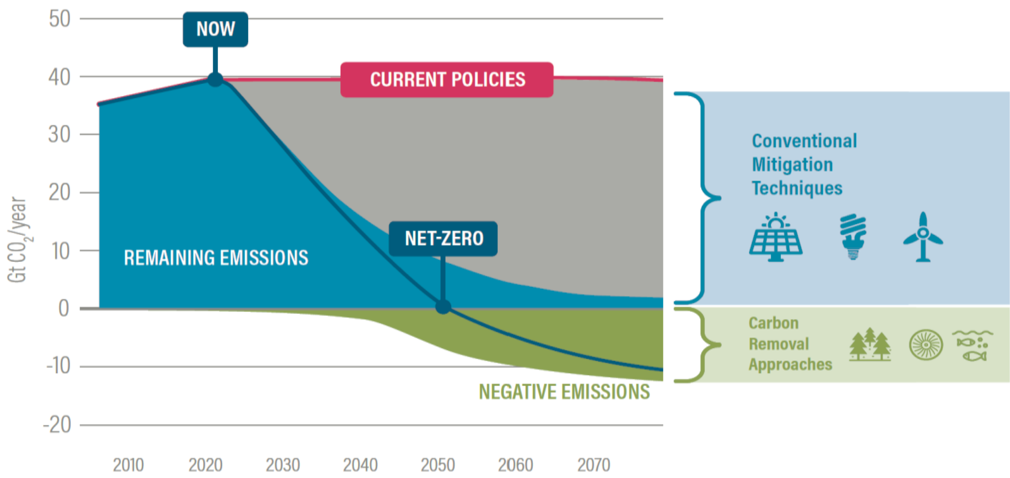
According to the Intergovernmental Panel on Climate Change (IPCC), under all emission scenarios, global surface temperature will continue to rise at least until the middle of the current century. Global warming of 1.5°C and 2°C will be exceeded in the 21st century itself, unless a deep reduction in CO_2 and other GHG happens in the coming decades.

With the earth's rising temperature a key worry, the Paris Agreement, a legally binding treaty on climate change, was adopted by 196 countries at the UN Climate Change Conference (COP21) in December 2015. **The Paris Agreement** has an over-arching goal to 1) hold the increase in the global average temperature well below 2°C above pre-industrial levels and 2) pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels by the end of this century.

To limit global warming to 1.5°C, emissions need to peak before 2025 at the latest and be reduced by ~43% before 2030, and reach net zero by 2050. As the issue requires immediate attention, many countries, state governments and corporates have announced net-zero targets in the recent years. As of October 2023, 97 parties, representing 101 countries and 81% of global GHG emissions, have communicated net-zero targets.

To reach net zero, the first priority will be to reduce as many human-caused emissions (from transport, industries, residences and others) to close to zero as possible. The remaining emissions would be balanced, with an equivalent amount of carbon removal from the atmosphere. The carbon removal would include afforestation and carbon capture and storage (CCS) directly from the atmosphere.

Exhibit 3: Path needed for staying below 1.5°C of temperature rise



Source: World Resource Institute; Kotak Institutional Equities

GHG emissions—fossil fuels are key culprit

To reduce greenhouse emissions most effectively in the coming years and decades, first we need to understand the key contributing segments. Overall, in terms of CO_2 equivalents, the world emits nearly 50 bn tons of GHG annually (~38 bn ton of CO_2, rest others).

Exhibit 4 illustrates the approximate breakdown of GHG emissions by key sectors. This indicates that nearly 3/4th of GHG emissions is from energy usage. The bulk of it comes from three sub-segments: 1) the transport sector (75% from roads, rest from other transport segments), 2) buildings (residential and commercial for fuel/electricity/cooling and heating needs) and 3) industries (mainly for energy usage).

In a few industrial processes such as cement manufacturing (while manufacturing lime from limestone) and chemical processes (such as making ammonia), CO_2 is emitted as a by-product of the manufacturing process.

Agriculture and forestry are also large sources of GHG emissions. Among these, livestock and manure are the biggest sources and are difficult to control. Animals (such as cattle and sheep) produce methane as part of their digestive process called enteric fermentation. Use of nitrogenous fertilizers and manures lead to large GHG emissions from soils.

Exhibit 5 shows the GHG emissions in terms of gases. CO_2 accounts for more than 3/4th of GHG emissions. CO_2, including methane (another carbon derivative), account for over 90% of GHG emissions. Thus, decarbonization is key to reducing GHG emissions and reaching net-zero targets.

Energy usage accounts for nearly 3/4th of GHG emissions

Exhibit 4: GHG emissions by sector (%)

	Sector	Sub-sector
Energy	73.2	
Transport		16.2
Buildings		17.5
Industry (fuel/energy)		24.2
Energy in Agri & Fishing		1.7
Unallocated fuel combustion		7.8
Fugitive emissions		5.8
Industrial processes	5.2	
Cement		3.0
Chemical & petrochemical		2.2
Agriculture, Forestry	18.4	
Livestock & Manure		5.8
Rice Cultivation		1.3
Agricultural Soils		4.1
Crop Burning		3.5
Forests/ crops/ grasslands		3.7
Waste	3.2	
Landfills		1.9
Wastewater		1.3
Total	**100**	**100**

Source: OurWorldInData.org, Kotak Institutional Equities

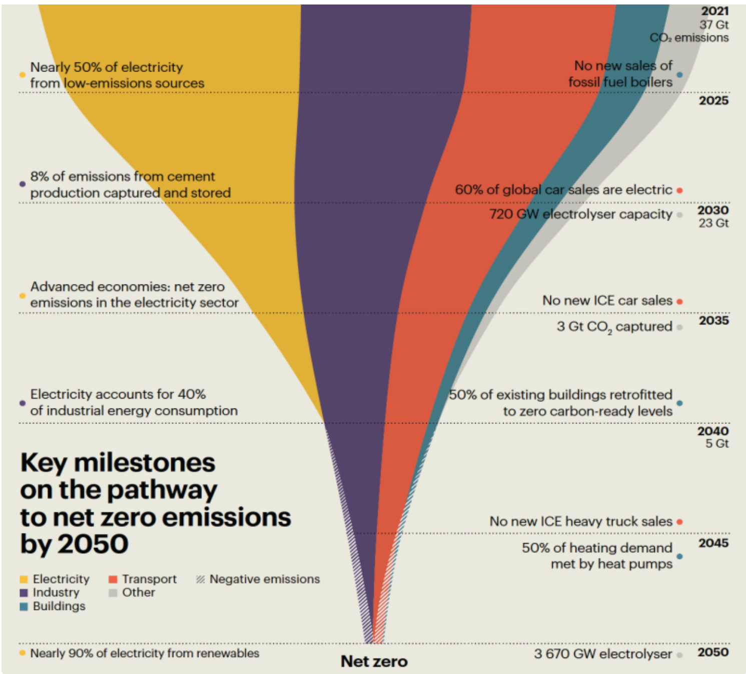
CO_2 accounts for 3/4th of GHG emissions

Exhibit 5: Global emissions in terms of gases

Carbon dioxide (CO2)	76
fossil fuels / industries	65
forest and other land usage	11
Methane	16
Nitrous oxide (N2O)	6
Fluorinated gases (F-gases)	2
Total	**100**

Source: EPA.gov, Kotak Institutional Equities

Exhibit 6: IEA's key milestones to net-zero emissions by 2050



Source: IEA's World Energy Outlook 2022; Kotak Institutional Equities

Hydrogen to play key role in decarbonization

The path to net-zero emissions will have a multi-pronged strategy to achieve emission reduction across a wide spectrum of sectors and fuels usage. There will be a large increase in clean-energy technologies. This will include those that are already developed such as solar and wind energy. It will also need the deployment of new emerging technologies. **The emphasis will be on end-use electrification and decarbonization of energy generation.** H_2 and hydrogen-based fuels will have a key role to play. Apart from direct use as a fuel, due to its unique properties, it will enable clean energy pathways across sectors.

Hydrogen as a fuel leads to zero-carbon emissions!

H_2 is the universe's most abundant material. In terms of specific energy (energy by weight), H_2's energy per kilogram is higher compared with other conventional fuels (3X of gasoline, 3.3X of diesel). Exhibit 8 shows that for each 1,000 kWh of energy, compared with 25 kg of H2, a much higher quantity of other conventional fuels are needed.

H_2 is also the simplest and the lightest molecule. One cubic meter of H_2 weighs just 89 grams. This means that in terms of energy density (energy by volume), H_2 has much lower energy. For this reason, either H_2 needs to be compressed at a high pressure (700 bars) or used in a liquid state at a cryogenic temperature ((-)253°C or 20 Kelvin). Though the handling may be difficult, zero-carbon emissions using H_2 as a fuel makes it a very attractive fuel.

For more details on H_2's key properties please refer to Annexure – 1.

H_2 has ~3X energy per kg versus gasoline, but for same energy, H_2 needs 3.5X-4X volume versus gasoline/diesel

Exhibit 7: Specific energy/energy density comparison, HHV (MJ/kg, MJ/liter)

	Specific Energy		Energy Density
	kWh/kg	MJ/kg	MJ/liter
Hydrogen	39.4	**142.0**	0.01 (1 bar) 7.10 (1,000 bar) 10 (liquid)
Methanol	5.6	20.0	15.9
Ammonia	6.3	22.5	15.6
Gasoline	13.1	47.3	35.0
Diesel	12.4	44.8	40.4
Heavy fuel oil	11.8	42.4	40.7
Biodiesel	11.7	42.2	33.0
Natural gas	14.4	52.0	0.04
LNG	14.4	52.0	22.2
Li-Ion batteries	0.28	1.0	2.8

Note:

(a) MJ = Mega Joule

Source: Kotak Institutional Equities estimates

With similar engine efficiency, per kg of H_2 will give over 4X distance versus per liter of petrol

Exhibit 8: Required quantity of fuels per 1,000 kWh of energy content (kg, liter, mmbtu or scm)

	per 1000 kWh	
Hydrogen	25	kg
Ammonia	160	kg
Gasoline	103	liter
Diesel	89	liter
Heavy fuel oil	88	liter
Natural gas	3.4	mmbtu
Natural gas	92	scm
CNG	69	kg

Note:

(a) 1 kWh = 3.6 MJ

Source: Kotak Institutional Equities estimates

H_2 leaves no carbon footprint

Exhibit 9: H_2 versus fossil fuel—carbon/H_2 content and CO_2 emission comparison

	Carbon content %	Hydrogen content %	CO_2 emission Kg/MWh
Coal	> 90	5-6	900
Petroluem crude	84 - 88	10-13	565
Natural gas	75 -77	20-25	365
Hydrogen	0	100	0

Source: Kotak Institutional Equities

Versatility makes H_2 a fuel of great hope

H_2 is already one of the most widely produced industrial gases in the world. Today, it is mainly used in the refining and fertilizers sectors, along with a few other sectors such as chemical and steel. As most production is from fossil fuels, the production of H_2 is one of the significant sources of CO_2 emissions in the world.

H_2 is also a fuel of great hope. Clean H_2 can be produced by using renewable energy, nuclear or fossil fuels with carbon capture. **If produced from renewable energy sources (such as wind or solar power), there are zero emissions in the production process called electrolysis**. In this process, about 50 units (kWh) and 9 liters of water produces 1 kilogram of "green" H_2. The potential for GH is much higher versus fossil fuels, as it is produced from solar and wind energy, which have much higher potential than the global energy demand.

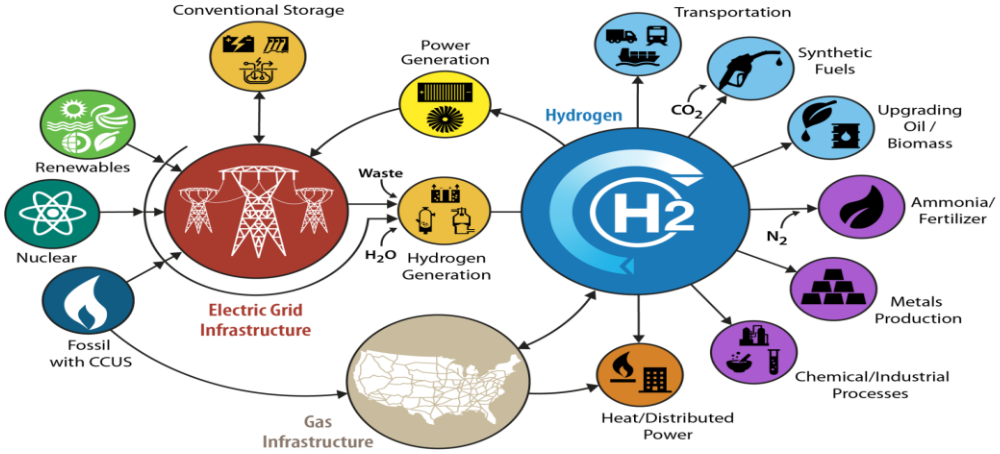
Importantly, in the reverse of electrolysis, H_2 can be used in a fuel cell to generate electricity with zero-carbon emissions. About 42 kg of H_2 can produce 1 megawatt-hour (1,000 units) of electricity at about 60% efficiency. It is one of the most versatile fuels and can help de-carbonize a range of sectors.

- Once produced at scale, green H_2 can be further **converted into other energy carriers** such as ammonia, methanol, methane and liquid hydrocarbon.
- H_2 can **be directly used in internal combustion engines** (such as gasoline and diesel) without causing any pollution.
- In a more efficient way, **H_2 can be utilized using fuel cells** to generate electricity. Fuel cells can be used for stationary applications in power plants and back-up generation to produce power on demand; it can also be used in a wide range of fuel cell electric vehicles (FCEVs).
- It can help in the **integration of renewables in energy systems**. H_2 made from renewables can be transported from regions with solar/wind capacities to demand centers.
- H_2 can be **blended with existing natural gas infrastructure** up to about 20% concentration without much change to infrastructure.
- It can be used to **produce synthetic fuels such as ammonia and kerosene** to power the shipping or aviation sectors.

Most new energy sources have limitations and do not provide flexibility, just as solar or wind power have intermittency issues and require the creation of additional transmission and storage infrastructure. **Given its multiple properties, H_2 can act as a connector, bringing together molecules and electrons**. It can connect producers and consumers; it also provides the benefit of renewable energy far away from the source of generation.

H_2 is key element among solutions to decarbonize world

Exhibit 10: H_2 enables clean energy pathways across sectors



Source: US Department of Energy, Kotak Institutional Equities

H_2's share in energy mix to grow multifold by 2050

IEA: With 6X rise in production, H_2 share in final energy demand to be ~13% by 2050

In its net-zero emissions (NZE) scenario, IEA expects the share of H_2 production to rise from 87 mt in 2020 by nearly 2.5X to 212 mt in 2030 and nearly 6X to 528 mt by 2050. For this level of production, the global electrolyzer capacity will rise from just 0.3 GW in 2020 to nearly 850 GW in 2030 and 3,600 GW in 2050.

Currently, nearly the entire H_2 production is consumed in refineries (40%) and industries (60%, mainly in the fertilizer and steel industry). In comparison, H_2 is expected to see much wider usage by 2050.

- Ammonia is primarily used as a feedstock for fertilizer. However, in a net-zero scenario, it will be used as a fuel in various energy applications. Ammonia could account for 45% of energy demand for the shipping sector. However, due to its toxicity, the wider use of ammonia will be limited.
- Synthetic kerosene made using H_2 and CO_2 (captured from atmosphere) could account for nearly a third of aviation fuel demand.
- Nearly 40% of H_2 production is expected to be used in the transport sector, **particularly in heavy and long-distance transport.** With the reduced consumption of fossil fuels, the H_2 usage in industry is expected to increase more than 3X. In addition, about 20% H_2 is expected to be used to generate electricity to balance increased generation from solar/wind power and for seasonal storage.
- **Overall, the IEA expects H_2 to account for 13% of final energy demand in 2050.**

Global H_2 production likely to rise 6X by 2050 and entirely produced from renewables; transport, industries and electricity will emerge as key users of H_2

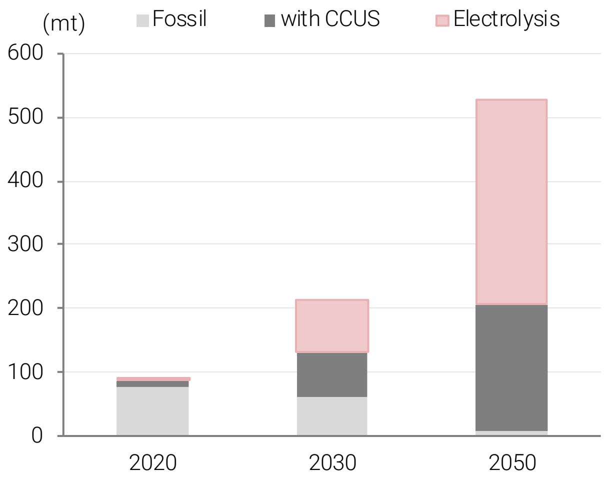
Exhibit 11: IEA's global H_2 production and sectoral consumption estimates

(million ton)	2020	2030	2050
Production of H_2 based fuels (mt)	**87**	**212**	**528**
Low-carbon hydrogen production	9	150	520
- share of fossil-based with CCUS (%)	95	46	38
- share of electrolysis-based (%)	5	54	62
Break-up of merchant vs onsite			
Merchant production	15	127	414
Onsite production	73	85	114
Consumption break-up of H_2 based fuels			
Electricity	0	52	102
of which hydrogen	0	43	88
of which ammonia	0	8	13
Refineries	36	25	8
Buildings and agriculture	0	17	23
Transport	0	25	207
of which hydrogen	0	11	106
of which ammonia	0	8	44
of which synthetic fuels	0	5	56
Industry	51	93	187

Source: IEA's NZE 2050, Kotak Institutional Equities

IEA's global H_2 production breakup (mt)

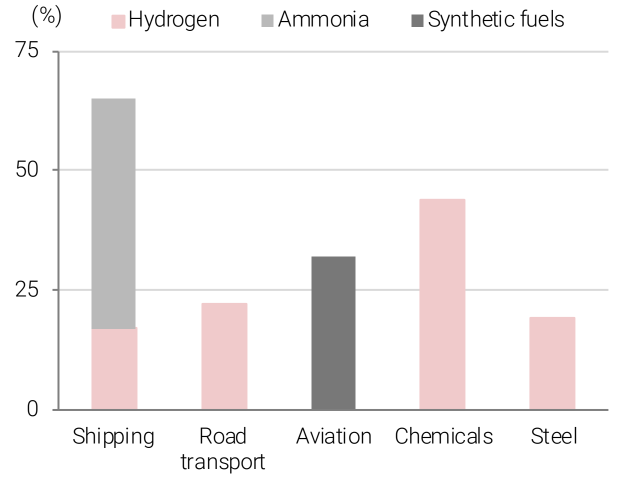
Exhibit 12: IEA's global H_2 production breakup (mt)



Source: IEA, Kotak Institutional Equities

H_2 will emerge as key fuel in several sectors

Exhibit 13: IEA's H_2 fuels demand by sector in 2050 (%)



Source: IEA, Kotak Institutional Equities

ETC sees even higher 15-20% H_2 share in final demand

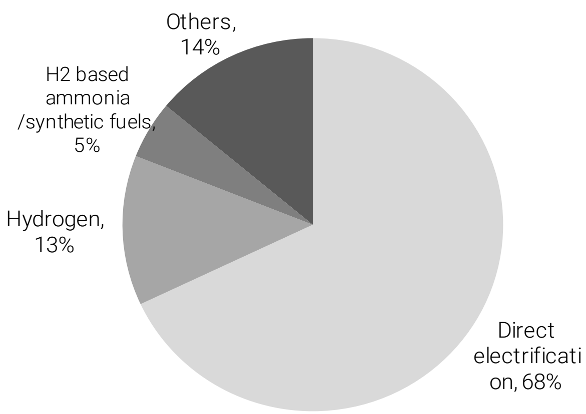
The Energy Transition Commission (ETC) is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by 2050, in line with the Paris climate objective.

The ETC expects H_2 to account for 15-20% global final energy demand by 2050, on the top of the close to 70% energy provided by direct electricity. It expects electricity generation that supports direct electrification to grow from 27,000 TWh (terra watt hours) to 90,000 TWh. It also expects H_2 use to rise from 115 mt (in 2019) to 500-800 mt by mid-century.

It expects ~85% H_2 to be produced through the green route, as GH becomes more efficient versus blue. For this production, there will be an additional electricity requirement of nearly 20,000 to 30,000 TWh of electricity.

Share of H_2 and its derivatives to rise to 15-20% and nearly 70% of final energy demand would be from direct electrification

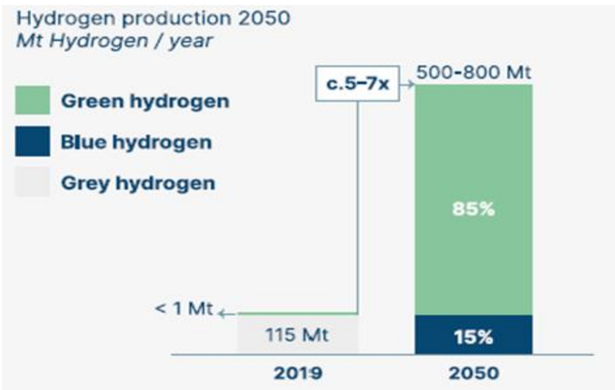
Exhibit 14: ETC's 2050 final energy demand scenario (%)



Source: Energy Transition Commission

H_2 production likely to rise 5-7X by 2050, share of green H_2 at 85% and blue H_2 at 15% according to ETC

Exhibit 15: ETC's H_2 productions estimates for 2050 (mt)



Note:

(a) According to IEA, in 2019, dedicated H_2 production was ~70 mt. The gap of 45 mt is due to H_2 production in several industrial processes such as catalytic naphtha reforming and chloralkali production.

Source: Energy Transition Commission

2

H_2 will get competitive, but not for mass transport

With countries and corporates racing to reach net zero, GH is getting a lot of attention. GH production is currently expensive and requires financial incentives/carbon tax on fossil fuels to spur adoption in hard-to-abate sectors. However, the popular target is to reduce GH cost by 80-85% over this decade to just US$1/kg. This will make GH cheaper versus grey/blue H_2 and other fossil fuels, further increasing its adoption. We note that despite the cost declining, there may still be a need for support such as incentive or carbon taxation for industries to switch to GH. However, much lower efficiency and difficulty in handling make GH-powered fuel cell electric vehicles (FCEVs) inferior to battery EVs (BEVs) used for mass transport.

GH production costs expected to decline

Although the policy environment and regulations will support GH, for usage to pick-up, the cost reductions will be a major driver. Though green H_2 costs have been declining, these are still higher by 2-3X versus blue H_2 at most places. The key drivers for cost reduction will be the decline in renewable power and electrolyzer costs. In addition, costs will decline due to improving efficiencies/increasing the lifetime of electrolyzers, economies of scale, learning rates and other such factors.

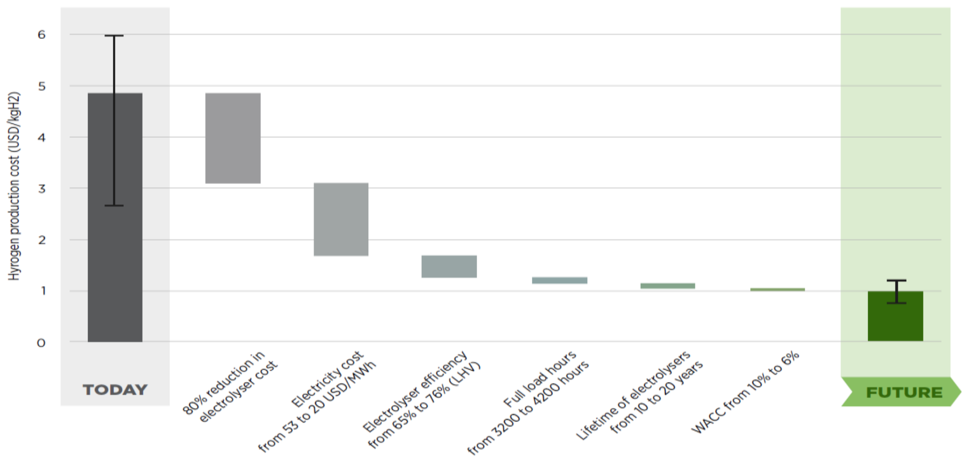
IRENA estimates GH costs to decline to US$1/kg by 2050

Exhibit 16 shows IRENA's potential GH costs reductions over 2020-2050.

- In the current scenario, key assumptions are electrolyzer cost of US$770/kW, efficiency of 65% (at lower heating value) and electricity price of US$53/MWh, with a full load for 3,200 hours (offshore wind) and a WACC of 10% (relatively higher risk).
- In the future scenario by 2050, IRENA expects electrolyzer costs to decline to US$130/kW (83% reduction), efficiency to rise to 75%, electricity price of US$20/MWh (62% reduction), full load for 4,200 hours (31% increase) and WACC of 6%.

Combination of cost reductions and efficiency/lifetime increases to lead reduction in green H_2 costs

Exhibit 16: IRENA's potential green H_2 cost reduction between 2020 and 2050 (US$/kg)



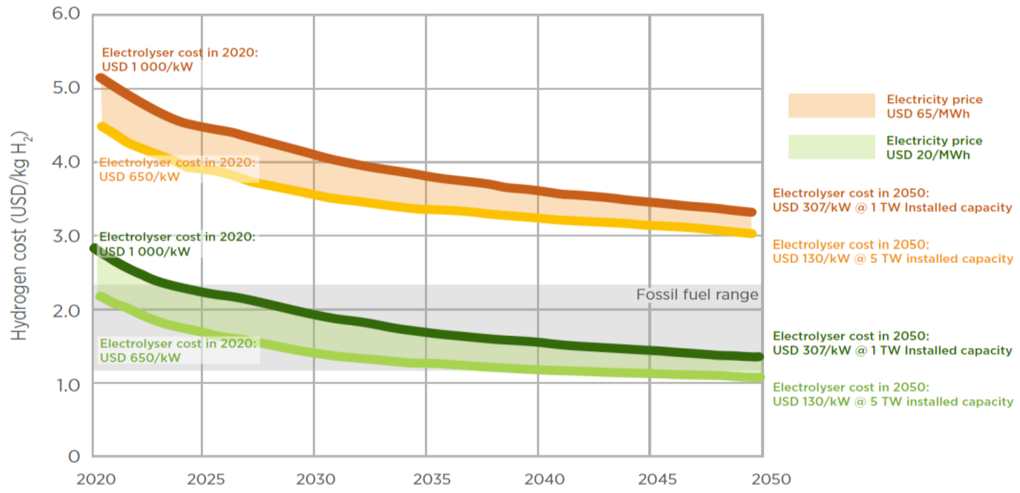
Source: IRENA—green hydrogen cost reduction, Kotak Institutional Equities

For GH costs to decline, the renewable power costs and electrolyzer prices will need to decline significantly. At low renewable electricity prices, aggressive deployment of electrolyzers, GH costs can fall to near US$1/kg by 2050.

Exhibit 17 shows IRENA's potential GH cost reductions for a range of electrolyzer costs and deployment levels at two electricity prices (average US$65/MWh, low US$ 20/MWh) over 2020-2050. In the best cast scenario, the lowest GH cost is already competitive versus fossil fuel-based production at lower electricity prices.

At low electricity price of ~US$20/MWh, GH is competitive

Exhibit 17: Cost of green H_2 production as function of electrolyzer deployment over 2020-2050



Note:

(a) Efficiency of 65% (LHV of 51.2 kWh/kg H_2) in 2020 and 76% (LHV of 43.8 kWh/kg H_2) in 2050

(b) Discount rate of 8% and stack lifetime of 80,000 hours

(c) Electrolyzer investment cost of US$650-1000/kW in 2020 and reaching to US$130-307/kW in 2050

Source: IRENA—green hydrogen cost reduction, Kotak Institutional Equities

DoE's H_2 shot targets H_2 cost of US$1 per 1 kg in 1 decade (1-1-1)

The US Department of Energy (DoE) has an initiative called Energy Earthshot. It aims to accelerate the breakthrough of more abundant, affordable and reliable clean energy solutions within a decade.

The first Energy Earthshot, launched in June 2021, is termed Hydrogen Shot. It seeks to reduce the cost of clean H_2 by 80% to US$1 per kilogram in 1 decade (1-1-1).

According to the DoE, achieving 1-1-1 goals can unlock new markets for H_2, including steel manufacturing, clean ammonia, energy storage and heavy-duty trucks. These goals can lead to at least a 5-fold increase in clean H_2 use and have a potential to reduce CO_2 emission by 16% before 2050.

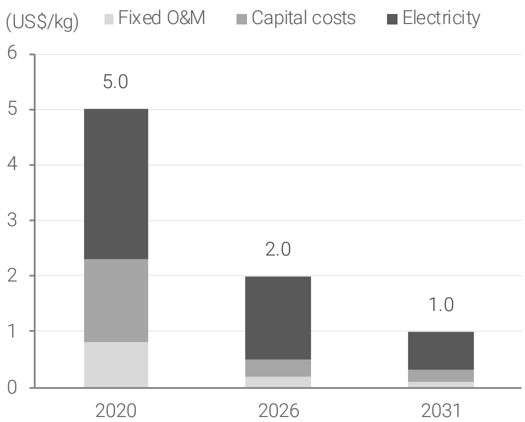
DoE targets clean H_2 costs of US$1/kg in 1 decade

Exhibit 18: DoE's Hydrogen Shot target

Source: US Department of Energy, Kotak Institutional Equities

Hydrogen Shot targets to cut capital/O&M costs by over 80-90%

Exhibit 19: Hydrogen Shot for clean H_2 cost (US$/kg)



Source: US Department of Energy, Kotak Institutional Equities

DoE's targets assume 85-90% reduction in stack and overall system capex versus 2022 levels

Exhibit 20: DoE's technical targets for PEM electrolyzer stacks and systems

		2022 status	2026 targets	Ultimate target
Stack				
Total Platinum group metal content (both electrodes)	mg/cm^2	3.0	0.5	0.125
	g/kW	0.8	0.1	0.03
Electrical efficiency	kWh/kg H_2	51	48	43
	(% LHV)	(65)	(69)	(77)
Average degradation rate	mV/kh	4.8	2.3	2.0
	(%/1,000 hours)	(0.25)	(0.13)	(0.13)
Lifetime	operating hours	40,000	80,000	80,000
Capital cost	**US$/kW**	**450**	**100**	**50**
System				
Energy Efficiency	kWh/kg H_2	55	51	46
	(% LHV)	(61)	(65)	(72)
Uninstalled capital cost	US$/kW	1,000	250	150
H_2 production cost	**US$/kg H_2**	**>3**	**2.0**	**1.0**

Source: US Department of Energy, Kotak Institutional Equities

Reliance has set a target of India achieving US$1/kg cost within a decade

In a September 2021 speech at the International Climate Summit, RIL Chairman had said that India can set an even more aggressive target of producing GH under US$1/kg within a decade. This will make India the first country to achieve the 1-1-1 target for H_2.

US$1/kg seems ambitious; electricity costs will need to fall sharply

As we highlighted earlier, to reach the target of GH price of US$1-2/kg, there will be a need for a sharp reduction of 80-90% in electrolyzer costs and overall system costs. Apart from the reduction in electrolyzer costs, there will be a need for further sharp reductions in renewable energy (RE) prices.

In Exhibit 21, we show the cost of electricity per kg of H_2 production at different energy prices. Currently, the efficiency of electrolyzers is 60-65%; this is likely to improve to 70-75% in the future.

With current RE prices in India of Rs2.5-3.0/kWh, we note that the cost of electricity itself is nearly US$1.6-1.9 per kg of H_2. With additional costs of US$2.5-3.0/kg for electrolyzer systems (fixed and variable), the production costs for GH are US$4-5/kg currently.

As electrolyzer technology evolves further, the electrolyzer efficiency is likely to increase to 75%. Still, to have H_2 costs at about US$2/kg, renewable electricity prices will need to decline to Rs1.5–2.0 per kWh (electricity cost would be US$0.8-1.0/kg of H_2).

For the H_2 **cost to decline to just US$1/kg, renewable power costs would need to decline to Rs1/kWh or even lower**. This, in our view, is ambitious and difficult in the near future.

Reduced prices of GH would increase the competitiveness with alternate fuels. However, as we highlighted above, a reduction in the renewable electricity price is a must for a reduction in H_2 prices. Thus, the competitiveness may not increase much in applications where electricity is alternate (such as BEVs versus FCEVs, as we discuss later in this note).

At current RE prices, cost of electricity itself is US$1.5-2/kg of H_2

Exhibit 21: Cost of electricity per kg of GH

Electricity cost	Current		Lower cost assumption		
RE price					
Rs/kWH	3.0	2.5	2.0	1.5	1.0
US$/MWh	37	30	24	18	12
Electrolyser efficiency %	65	65	75	75	75
Per Kg of Hydrogen					
Electricity needed (kWh)	51	51	44	44	44
Electricity cost (US$/kg)	**1.9**	**1.6**	**1.1**	**0.8**	**0.5**

Source: Kotak Institutional Equities estimates

GH will likely get cheaper versus gray/blue H_2

Exhibit 22 shows BloombergNEF's estimate of GH costs versus gray and blue H_2 for 2023. For gray H_2, the estimates of costs are in the range of US$1.0-2.9 per kg. For blue H_2, the cost estimates are higher at US$1.8-4.7/kg. For GH, the cost is higher at US$4.5-12.0 per kg. For each country, it is estimated that the GH cost is higher versus gray H_2.

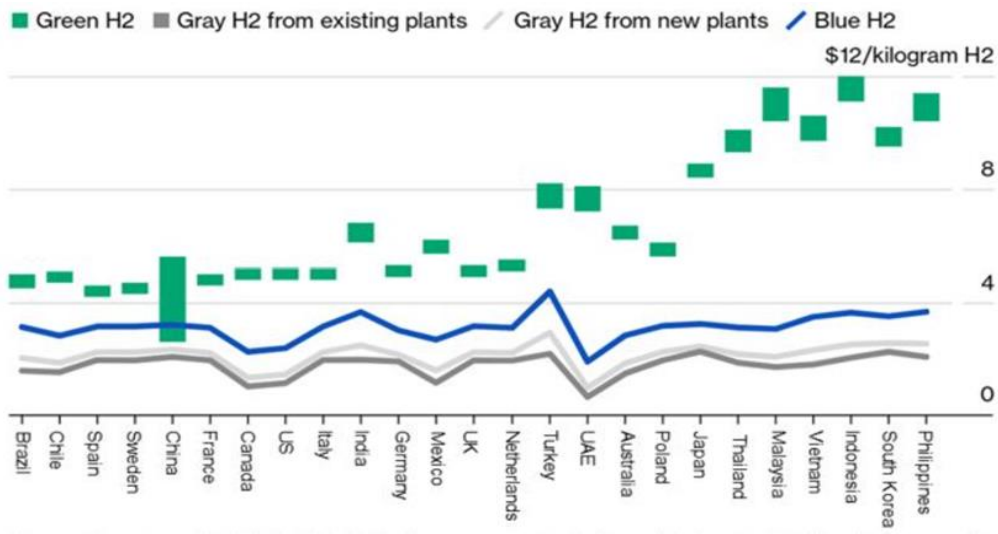
Yet, by 2030, producing GH from a new plant would be as much as 18% cheaper than continuing to run an existing gray H_2 plant in five major countries. For five countries, i.e., Brazil, China, India, Spain and Sweden, it expects GH from a new plant to start undercutting gray H_2 from existing plants by the end of this decade.

In the longer run, the cost of GH is also likely to decline even below the price of gray H_2 in regions with relatively lower costs of renewable energy generations. The production of gray H_2 will likely be fully eliminated. However, blue H_2 production is likely to continue, especially in the areas that have low gas costs (such as the Middle East or the US) and where methane/CO_2 leakage is significantly reduced (Exhibit 23).

According to the ETC, even with 95% carbon capture, blue H_2 results in 0.4 ton of uncaptured CO_2 per ton of H_2. In addition, at the current average of 1.5% methane leakage from the global natural gas industry, there will be an additional 3 ton of CO_2 equivalent emission per ton of blue H_2.

Current green H_2 costs much higher versus gray and blue H_2, but this may change soon

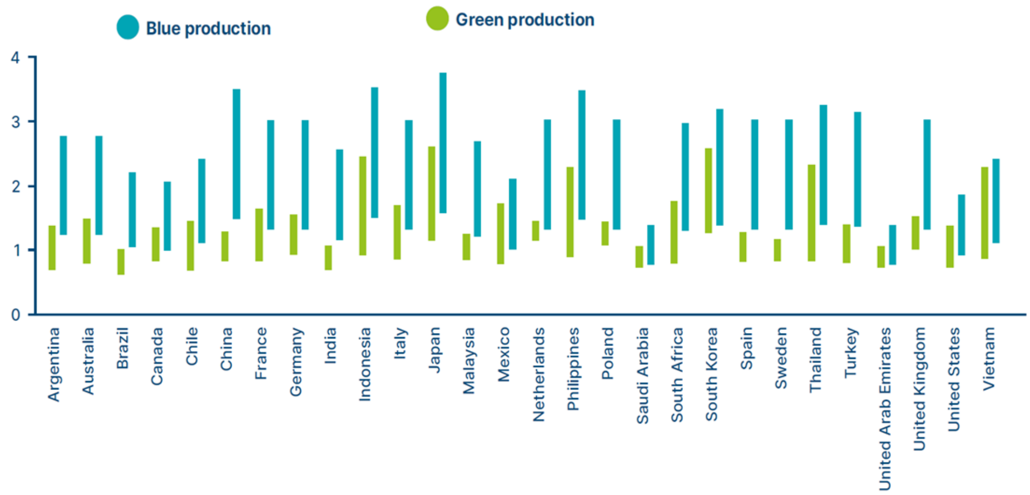
Exhibit 22: Levelized cost of H_2 in 2023 (US$/kg)



Source: BloombergNEF, Kotak Institutional Equities

GH production likely to get cheaper versus blue H_2 in most regions by 2050

Exhibit 23: Cost of green and blue H_2 production in 2050 (US$/kg of H_2)



Notes:

(a) Blue production prices are for blue H_2 production in 2020 +/- 50%

(b) Green production prices are 2050 levelized costs (LCOE) for low to high prices of PV and offshore wind

Source: Energy Transition Commission, BloombergNEF, Kotak Institutional Equities

Even at US$1/kg, H_2 may need support such as fiscal incentives/carbon taxation

As we highlighted in the previous section, there is large potential for cost reduction in the production of GH. Over the next few years, GH production costs would decline below blue H_2 in several areas and eventually, it will be lower versus even gray H_2 production costs. Programs such as Hydrogen Shot have an ambitious target to reduce H_2 costs by about 80% to just US$1/kg in a decade.

However, it needs to be noted that despite such sharp reduction in costs, replacing conventional fossil fuels by H_2 (or its derivative) will entail higher costs. These costs, though significant, can be seen as the cost of reducing carbon emissions, if conventional fossil fuels were used. For example, the cost of synthetic ammonia produced using US$1/kg H_2 will be nearly 55% higher versus VLSFO; it would be at par with VLSFO only at the H_2 price of US$0.5/kg.

Thus, **even at a H_2 cost of US$1/kg, a carbon taxation on fossil fuel usage is required** to bridge the cost gap.

Even at very low green H_2 costs, most H_2 technology will likely be expensive versus fossil fuels

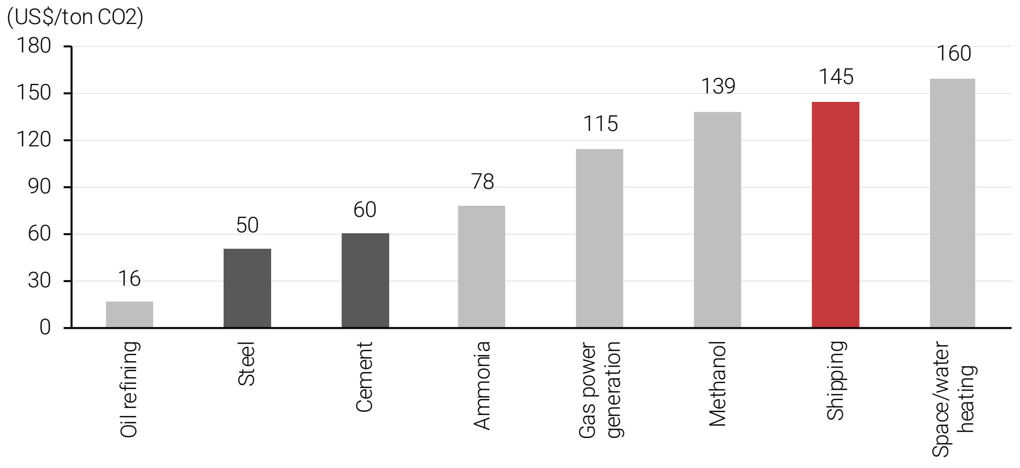
Exhibit 24: Cost premium for using H_2 as fuel versus fossil fuels (%)

(% premium)	Hydrogen price (US$/kg)		
	2.0	**1.0**	**0.5**
Synthetic jet fuel	130	65	30
Green Ammonia			
- for shipping	170	55	3
- for fertilisers	45	3	(15)
Green steel	40	23	15

Source: Energy Transition Commission, WEF and Mckinsey for Clean Skies for Tomorrow, Kotak Institutional Equities

Carbon penalties will be required to make H_2 competitive versus fossil fuels even at US$1/kg price

Exhibit 25: Carbon penalty required for green H_2 to be competitive versus fossil fuels in 2050 (US$/ton CO_2 equivalent)



Note:

Comparison with 1) coal for steel/cement, 2) fuel oil for shipping and 3) natural gas for others

Source: Energy Transition Commission, BloombergNEF, Kotak Institutional Equities

ZEVs: H_2 may not catch up with BEVs for mass transportation

Zero-emission vehicles (ZEVs) are those vehicles that do not lead to any emissions during vehicle operations such as battery electric vehicles (BEVs) or H_2-based combustion engines (H-ICE) or fuel cell electric vehicles (H-FCEVs). At COP-27 in November 2022, the Accelerating to Zero (A2Z) coalition was launched to secure more ambitious commitments to a ZEV transition aligned with the Paris Agreement.

- For developed countries, the A2Z declaration requires stakeholders to work toward all sales of new cars and vans being zero-emission by 2040 or earlier or by no later than 2035 in leading markets.
- For emerging markets and developed economies, it requires stakeholders to work intensely toward accelerated proliferation and adoption of zero-emission vehicles. India is also a signatory in this category.

With the goal of making tail-pipe emissions zero, there is increasing focus on finding alternatives to the conventional internal combustion engine vehicle. In recent years, battery electric vehicles (BEVs) have emerged as a front-runner to replace conventional internal combustion engine (ICE) vehicles.

Though BEVs have seen early success, there are several concerns as well. These include: 1) lithium and cobalt reserves are limited and are found only in a few countries; cobalt is primarily produced in Congo; apart from environmental concerns, there have been concerns on child labor as well; lithium is mainly found in Chile and Australia, 2) there are concerns on the disposal of batteries and recycling is expensive and 3) existing electricity grids are not designed to handle extra loads; there will need to be significant investments in upgrading grids, apart from creating renewable capacity.

H_2 is another pathway for getting zero tailgate emission. H_2 can be directly used in a combustion engine (H-ICE) similar to a petrol or diesel engine. This method can result in early adoption of H_2 vehicles, particularly for heavy vehicle fleets. Vehicles that run on H_2 fuel cells (H-FCEVs) are another and rather more efficient method for vehicles that require lower load.

Overall efficiency of H2 vehicles much lower versus BEVs:

For the transport chain to be zero polluting, apart from the vehicle itself being zero emission, it is necessary to have renewable energy as a source of electricity or H2. In Exhibit 26, we compare if the same quantum of renewable solar or wind power was used (100 kWh) to determine the ultimate energy available to wheels.

In case of electricity, there is about 8-10% of T&D losses and nearly 90% energy is available. In contrast, for H_2 vehicles, H_2 fuel will need to be made either near the source of power generation or closer to the consumption center. At the current stage, the electrolysis process is only about 65-67% efficient. Thus, for each kg of H_2 (LHV 33.3kWh), nearly 50 kWh of electricity will be needed. In addition, there will be about 10% loss (either transmission or H_2 logistics including boil-off). Thus, compared with the 90 kWh energy available to vehicles in the case of BEVs, it will be only about 60 kWh for H_2 vehicles.

Electric motors are typically very efficient in converting electric power into motion. Including the energy recuperation from regenerative breaking, the efficiency is 93-95%. Including the losses in battery and rectifier losses (DC/AC conversion), overall, about 77 kWh energy is available to wheels.

The H_2 combustion engine similar to ICE has a low efficiency of only ~40%. Including about 10% energy loss in transmission assembly, only about 22 kWh energy is available to wheels. This implies nearly 78% losses from renewable energy generation and only 36% conversion of energy from tank to wheel.

Compared with combustion engines, fuel cells are more efficient and have an efficiency of about 60%. Assuming similar losses for electric motor transmission and rectification, there is only 33 kWh energy available to wheels.

Lower overall efficiency implies that for a similar amount of road-km travelled, compared with BEVs, the need to set up renewable power will be much higher for H_2 vehicles, at nearly 2.0-2.5X for H_2 FCEV and higher 3.5-4.0X for H_2 combustion engines.

Among the two H_2 options, the efficiency of the fuel cell option is higher versus the combustion engine. However, fuel cells will be much higher priced and will have less durability (before needing replacement).

EVs have much higher overall energy efficiency versus H_2 fuel-based vehicles

Exhibit 26: Generation to wheel efficiency comparisons (kWh, %)

		H-FCEV	H-ICE	BEV
Renewable Energy	**kWh**	**100**	**100**	**100**
Electroysis loss	%	33	33	—
Transport / T&D losses	%	10	10	10
Energy in tank/ battery	kWh	60	60	90
Fuel Cell effficency	%	60		
Combusion efficiency	%		40	
Battery losses	%			5
Rectifier efficency	%	97		97
Electric motor/transmission efficiency	%	93	90	93
Actual available to wheels	**kWh**	**33**	**22**	**77**
Tank to wheels	%	54	36	86

Source: Kotak Institutional Equities estimates

Opex per km low for H-ICE; comparable for H-FCEV and BEVs

Exhibit 27 gives a comparison of H2 vehicles with fuel cells, H2 vehicles with combustion engine and BEVs for other key comparable features.

For H_2 vehicles, the costs and weights are based on a 130-kW drive train, with 75 kWh of energy stored and 75 kW of recuperation power. The technology costs are based on production rate of 100,000 vehicles per year.

Although the lifecycle of fuel cells and combustion engines is measured in hours, the battery life is usually measured in terms of charge/discharge cycles. As fuel cells have lower recycles, these can have operating hours of 2,000 to 3,000 hours. Fuel combustion engines can have an operating life of 7,000 to 8,000 hours. Electric cars such as Tesla Model 3 can have up to 1,500 charging cycles, with an average range of 500 km per charge. So, at an average speed of 70 km/hour for all three vehicles, these could have nearly 8,000 operating hours. Conservatively, we have assumed 5,000 operating hours for the H_2 combustion engine and BEVs.

For BEVs, we have assumed a cost of new 75 kWh battery at US$150/kWh. This makes the overall cost of fuel/battery assembly of EV at about US$12,200, which is much more expensive versus H_2 ICE (US$6,200) or H_2 FCEV (US$8,400).

Exhibit 27: Comparison of H_2 (fuel cell and combustion engine) and BEVs

	H-FCEV		H-ICE		BEV	
Operating hours	2,000		5,000		5,000	
Operating km	140,000		350,000		350,000	
Relative costs	Electric Motor (US$/KW)	7-8	Engine/Transmission (US$/KW)	30 -35	Electric Motor (US$/KW)	7-8
	Fuel cell (US$/KW)	41-48	H_2 Storage (US$/KWh)	15 -16	Batteries (US$/kWh)	150
	H_2 Storage (US$/kWh)	15 -16				
Power/energy densities	Fuel cell (kW/kg)	2.0	Combustion engine (kW/kg)	1.5	Electric Motor (kW/kg)	5.0
	Electric Motor (kW/kg)	5.0	Compressed H_2 (kWh/kg)	1.6	Batteries	0.3
	Compressed H_2 (kWh/kg)	1.6				
Total cost for operations (US$)	Fuel cell	6,000	Engine/transmisssion	4,200	Batteries (75 kWH)	11,250
	Electric motor	1,000	Electric motor	550	Electric motor	1,000
	Hydrogen storage	1,100	Hydrogen storage	1,100		
	Supercapacitor	325	Supercapacitor	325		
	Total	**8,425**	**Total**	**6,175**	**Total**	**12,250**
Operating cost (excluding H_2 or electricity cost)	US cents /km	**6.0**	US cents /km	**1.8**	US cents /km	**3.5**
Weight in kg (130 kW drive train)	Fuel cell	65	Combustion engine	87	Batteries	300
	Air Compressor	10	Transmission	40	Electric motor	25
	Electric motor	26	Electric motor	15		
	Hydrogen storage	47	Hydrogen storage	47		
	Supercapacitor	4	Supercapacitor	4		
	Total (kg)	**148**	**Total**	**193**	**Total**	**325**
Advantages	- No emissions		- Use of existing manufacturing facilities, - No CO_2 emissions - Simple to recycle		- No emissions	
Disadvantages	- Limited lifetime of the fuel cell - Fuel cell aging leads to higher fuel consumption - Battery needed for warm-up during winters		- Lowest efficiency - Electric motors used only for recuperation - Nitrogen oxide emissions - High maintenance needs - Lubes consumption		- No weight loss during driving - Capacity fades over the lifetime - High weight - Battery recycling a challenge	

Source: Handwerker, M; Wellnitz, J; Marzbani, H—Comparison of Hydrogen Powertrains with the Battery Powered Electric Vehicle and Investigation of Small-Scale Local Hydrogen Production Using Renewable Energy. Hydrogen 2021, 2, 76-100. https://doi.org/10.3390/hydrogen2010005; Kotak Institutional Equities estimates

Due to the overall lower costs of combustion engines and running life similar to EV, the per km cost of the fuel system of a combustion engine (excluding fuel or electricity costs), at about US 2 cents/km, is the lowest. However, compared with FCEVs, the fuel system costs for BEVs are significantly lower. We do note that as FCEVs are still at a relatively earlier stage (versus BEV) and cost declines will likely be faster due to learning curve benefits and economies of scale.

Apart from lower operating costs (excluding fuel), the key advantage of H-ICE vehicles is that these would use existing manufacturing facilities, leading to faster adoption. **Lower overall costs make H-ICE vehicles particularly suitable for heavy-duty vehicles.** For such vehicles, apart from the higher price, the other key drawback of BEVs is their higher weight for a similar range. Moreover, the vehicle does not lose any weight while driving, as battery weight will not change.

Although the H_2-based FCEV seems competitive versus BEVs on cost of operations (excluding fuel), the key drawback is the more complicated handling requirements for H_2. Liquid H_2 storage is not feasible for mass transportation due to the requirement of low cryogenic temperatures ((-)253°C).

During the early phase of BEV, the existing grid infrastructure can handle the additional load for charging EVs. However, the grids will need to be upgraded for wider adoption of BEVs.

FCEVs may not compete with BEVs for mass transportation

Exhibit 28 shows our estimated working for fuel costs for Toyota Mirai (a H-FCEV) and Tesla Model 3 (a BEV). Mirai has a H_2 tank capacity of 5.8 kg and range of nearly 402 miles or 650 km. Tesla 3, with a 75-kWh battery has a range of about 315 miles (507 km) for its performance variant.

In Exhibit 28, we estimate the per km running-cost for both these variants. For BEVs, we assume an electricity price of US 10-12 cents/kwH (Rs8-10/kWh); for H_2, we assume a price of US$4-5/kg. At these prices, the per km fuel/energy costs are significantly lower for BEVs versus H_2 vehicles.

Over the next few years, the costs of renewable electricity for BEVs and H_2 for FCEV are expected to decline. With relatively more mature technologies, the likely decline in electricity costs should be lower compared with H_2 production costs. However, even if H_2 costs decline to an ambitious US$1/kg, the **cost per km for FCEVs is unlikely to be cheaper versus BEVs.**

At current prices, operating costs for FCEVs are higher versus BEVs; FCEVs may not be cheaper, even if H_2 costs decline to US$1-2/kg

Exhibit 28: Overall fuel system costs comparison for FCEV and BEV, US$ or cents/km; Rs/km

		Toyota Mirai (FCEV)					Tesla Model 3 (BEV)				
Fuel capacity (kg / kWh)				5.8	kg				75.0	kwh	
Range (km)				640					507		
Price in US$/cent			**likely**		**current**			**likely**		**current**	
Hydrogen price	US$/kg	1.0	2.0	3.0	4.0	5.0					
Electricty price	cent/kWh						4.0	6.0	8.0	10.0	12.0
Full tank/battery price	US$	5.8	11.6	17.4	23.2	29.0	3.0	4.5	6.0	7.5	9.0
Fuel cost	cents/km	0.9	1.8	2.7	3.6	4.5	0.6	0.9	1.2	1.5	1.8
Other fuel system cost	cents/km			6.0					3.5		
Overall fuel plus fuel system costs	**cents/km**	**6.9**	**7.8**	**8.7**	**9.6**	**10.5**	**4.1**	**4.4**	**4.7**	**5.0**	**5.3**
Equivalent price in Rs											
Fuel price per kg or kWh	Rs	83	166	249	332	415	3.3	5.0	6.6	8.3	10.0
Tank filling/battery charging	Rs	481	963	1,444	1,926	2,407	249	374	498	623	747
Fuel cost	Rs/km	0.75	1.5	2.3	3.0	3.8	0.5	0.7	1.0	1.2	1.5
Other operating cost Rs/km				5.0					2.9		
Overall fuel plus fuel system costs	**Rs/km**	**5.7**	**6.5**	**7.3**	**8.0**	**8.8**	**3.4**	**3.6**	**3.9**	**4.1**	**4.4**

Notes:

(a) For other fuel system costs, please refer to previous exhibit

(b) Assumed exchange rate of Rs 83/USD

Source: Kotak Institutional Equities estimates

In addition to being relatively cheaper versus H_2-based FCEVs, BEVs have the key advantage of ease of handling for mass transport. More complicated handling (either cryogenic or compressed) and risk of leakage/accidents make H_2 less suitable for mass adoption in the short to medium term, in our view.

The key drawback of BEVs will be the need to upgrade existing transmission and distribution infrastructure as BEVs scale up. Though H-FCEV would not need similar investment in distribution infrastructure, they will need the creation of a new H_2 distribution system. Though these are likely cheaper, these would still be complicated. As we noted earlier, due to the lower efficiency of FCEV systems, the need for creating renewable generation capacity will be far higher for FCEVs versus BEVs, in our view.

Hydrogen deployment likely slow and only in few areas

As we highlighted earlier, H_2 is one of the most versatile fuels and can help mitigate concerns around GHG emissions and global warming. Though H_2 can be used in most applications, despite a likely sharp reduction in prices over the coming years, it may not be the most suitable or competitive fuel for all applications.

Likely deployment and competitiveness of H_2 in key usage

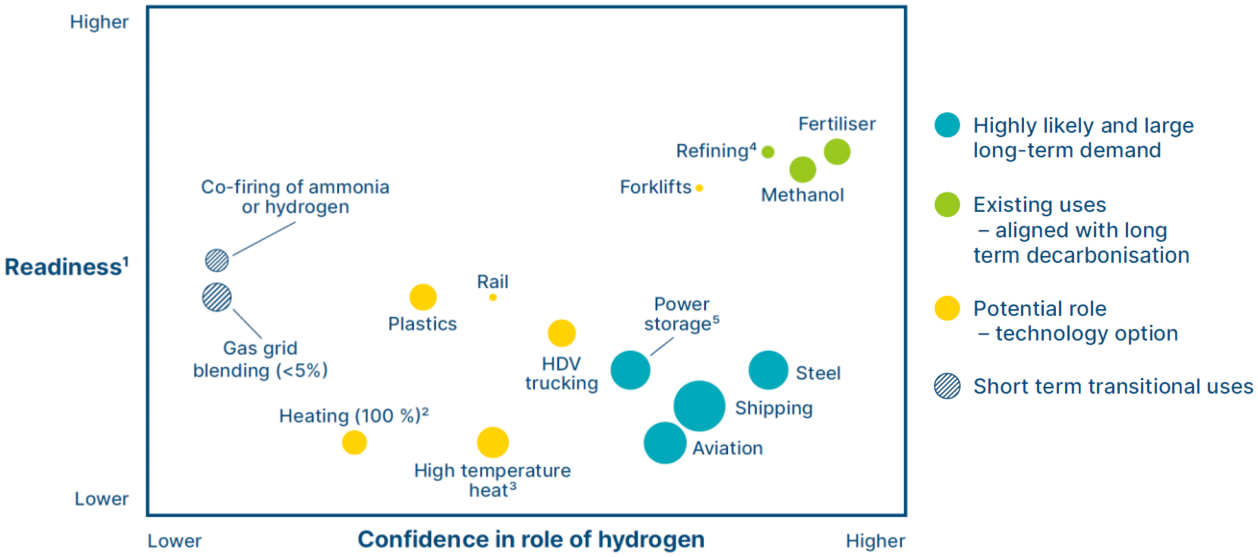
Exhibit 29: Likely competition of different fuels for key user categories

Sector	Use-case	2020s	2030s	2040s
Transport	Light passenger/ freight	BEVs		
	Short-distance HDVs	BEVs catching up with ICE	BEVs	
	Very long-distance HDV	ICEs	FCEVs and BEVs catch up with ICE.	FCEVs > ICE > BEVs
Industry	Ammonia / Steel / Refinery H2 demand	Fossil fuels better. Green H2 getting competive	GH competitive for ammonia, refinery; partly for steel	GH most competitive
	Methanol	Fossil fuels	Fossil fuels competitve. GH partially so.	
	Industrial heat	Fossil fuels > direct electrification	Fossil fuels competitive. Electrification increasingly competitive	Fossil fuels. H_2 / direct electrification partly competitive
Electricity storage	Short-term (daily) storage	Li-ion batteries competitive		
	Longer (weekly/ monthly/ seasonal) storage	LT balancing with fossil and hydro. LT storage needs minimal.	H_2 getting competitive. Need low as wind/solar still below 60-80%	H2 competitive. LT storage required in a high wind and solar system

Source: TERI, Kotak Institutional Equities

There will be multiple potential usage of H_2 in several sectors; some of these can provide initial impetus for developing markets

Exhibit 30: Potential usage for H_2



Note:

(a) Readiness refers to combination of technical readiness, economic competitiveness and ease of sector to use H_2

(b) Heating (100%) refers to building heating with H_2 boilers

(c) High temperature heat refers to industrial heat process above 800°C

(d) Current usage in refining higher due to higher oil consumption

(e) Long-term H_2 usage for energy storage

Source: Energy Transition Commission

3

India: High potential for H_2 growth

Although India's per capita emission is about half of the global average, due to the sheer size of its population, it is the world's third-largest emitter of GHGs. The Indian government has shown a commitment to a low-carbon development strategy. India's renewable energy prices are among the lowest in the world. The government's target of 500 GW of non-fossil energy by 2030 will likely enable sufficient renewable energy generation for the country to scale up its GH production. Initial impetus for growth will likely come from the fertilizer and refinery sectors, where the government will likely mandate gradual GH obligation. As GH costs decline, GH usage could diversify into other segments such as the steel industry, heavy-duty vehicles and even transport. Niti Ayog estimates that India's H_2 usage will increase over 4X by 2050.

India is the third-largest GHG emitter, but committed to low-carbon development strategy

At ~2.5 ton of CO_2 equivalent (tCO_2e), India's per capita emission is significantly below the global average of 4.8 tCO_2e. However, due to the sheer size of the population, with nearly 3,200 million tCO_2e ($mtCO_2e$), India is the third-largest emitter of GHG (after China and the US). With nearly 17% of the global population, India contributes nearly 6.8% to global emissions (according to Climate Watch data).

As a developing country with a large population, India has significant energy needs for its development. However, over the years, it has been making efforts at climate actions across the entire economy. India has a track record of meeting its earlier commitments at the United Nations Framework Convention on Climate Change (UNFCCC), the key multilateral agency on climate action, and under the Paris Agreement.

At the 26th session of the Conference of Parties (COP 26) of UNFCC, **India has set five targets** (termed Panchamrit or five nectar) of 1) 500 GW of non-fossil energy by 2030, 2) 50% energy requirement from renewables by 2030, 3) reduction in projected carbon emissions by 1 bn tons by 2030, 4) reduce carbon intensity of economy by 45% by 2030 over 2005 levels and 5) target of net zero emission by 2070.

Energy usage accounts for India's 3/4th GHG emissions

Exhibit 31: India's GHG emission sector break-up (%)

GHG sources	sector	sub-sector
Energy	**75.0**	
Energy industries		42.5
Manufacturing		14.0
Transport		9.7
Others		7.5
Fugitive emission		1.3
Industrial process	**8.0**	
Mineral industry		4.8
Chemical industry		0.9
Metal industry		1.4
Others		1.7
Agriculture	**14.4**	
Enteric fernmentation		7.8
Manure management		1.0
Rice cultivation		2.5
Agricultural soils		2.7
Others		0.3
Waste	**2.7**	
Solid waste disposal		0.6
Waste-water handling		2.1
Total	**100.0**	**100.0**

Source: MoE&F's 3rd Biennial update to UNFCCC; Kotak Institutional Equities

India has strong commitment for climate action in COP26

Exhibit 32: India's "Panchamrit" plan for decarbonization

1) **500 GW non- fossil energy capacity by 2030**
2) 50% of India's energy requirements from RE by 2030
3) Reduction in total projected carbon emissions **by 1 bn tons between 2022 to 2030**
4) **45% reduction in carbon intensity** of the economy by 2030, over 2005 levels
5) Target of **net zero emissions by 2070**

Source: MNRE; Kotak Institutional Equities

Apart from the climate action targets mentioned above, India has also **set a target to become energy independent by 2047**. Already in recent years, India has emerged as one of the fastest-growing renewable energy capacity markets in the world and stands among those countries with the cheapest cost of production. India aspires not only to grow its domestic GH market, but aspires to produce GH for the world and become a H_2 hub. Over the past two years, India has announced the National Green Hydrogen Mission (NGHM) and several new policies and incentives that we discuss below.

India's H_2 demand can increase over 4X by 2050

In India, H_2 is currently used mainly 1) in refineries for processes such as desulphurization, hydro-treating, hydrogenation and hydro-cracking, 2) as feedstock in the production of ammonia-based fertilizers and 3) as feedstock in methanol production. Nearly all H_2 usage is gray H_2 produced using natural gas.

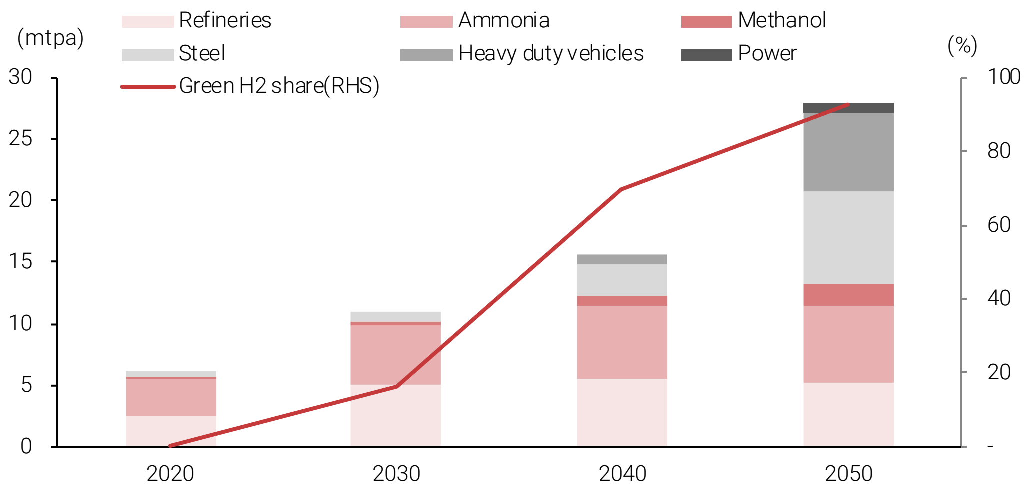
In 2020, India's H_2 demand stood at 6 mtpa (largely gray H_2, with an equal split between refining and ammonia production). Exhibit 33 gives India's H_2 demand outlook, as given by a 2022 report "Harnessing Green Hydrogen" by Niti Aayog in collaboration with RMI. This projects H_2 production to increase to ~11 mtpa by 2030 and increase over 4X to ~29 mmtpa by 2050.

It also estimates that on a price parity basis alone (without any policy intervention), from negligible currently, the share of green H_2 will increase to 16% by 2030 (or about 1.7 mmtpa) and rise to nearly 94% by 2050. Similar to mature markets, it expects India's initial demand growth to be driven by hard-to-abate sectors such as refinery, ammonia and methanol. Over the longer term, it expects steel and heavy-duty trucking to drive majority of growth accounting for over 50% of demand by 2050.

We note that compared with about 1.7 mmtpa GH usage according to Niti Aayog/RMI estimates (in no policy intervention scenario), India's NHGM target is far more aggressive at 5 mmtpa GH by 2030.

India's H_2 demand could increase over 4X by 2050

Exhibit 33: India's H_2 demand outlook and potential green H_2 share (mmtpa, %)



Source: Niti Aayog, RMI, TERI, Kotak Institutional Equities

To boost green H_2 demand, **Niti Aayog suggested setting up a visionary target complemented by strict mandates and adequate viability gap funding for addressable demand**. It also suggested clear mandates for H_2 blending, to provide demand for early green H_2 projects and encourage market development.

- **For refineries**, it suggested a mandate of **50% GH blending by 2030**, with a cut-off of 2040 for 100% blending.
- **For the fertilizer** sector, it had suggested **100% import substitution by 2030**. However, as we note in the next chapter, NHGM has set up a target of 2034-35 for 100% import substitution. It suggested that the sector should go 100% green by 2040.

Exhibit 34: Niti Aayog's suggested aspirational targets for new green H_2 applications

Sector	Type	Target
Steel	Old plants	Fleet level carbon intensity less than 2 ton CO2/ton of steel by 2035
	New capacity	At least 20 mtpa of green H2 based green steel to be made for exports
CGDs	Pilot and subsequent scale-up	10% blending by 2025 and 20% by 2030
Green Ammonia	Exports	25 mtpa of exports to countries such as Japan, Korea and the EU
Heavy-Duty Vehicles (HDVs)	Pilots on specific routes	Pilot of 1,000 trucks, 50 boats, 10 aircrafts by 2030. Three hydrogen corridors to be developed.
Power	Participation in RTC tenders	Allow hydrogen to compete with other storage technologies in SECI's RTC tenders.

Source: Niti Aayog, Kotak Institutional Equities

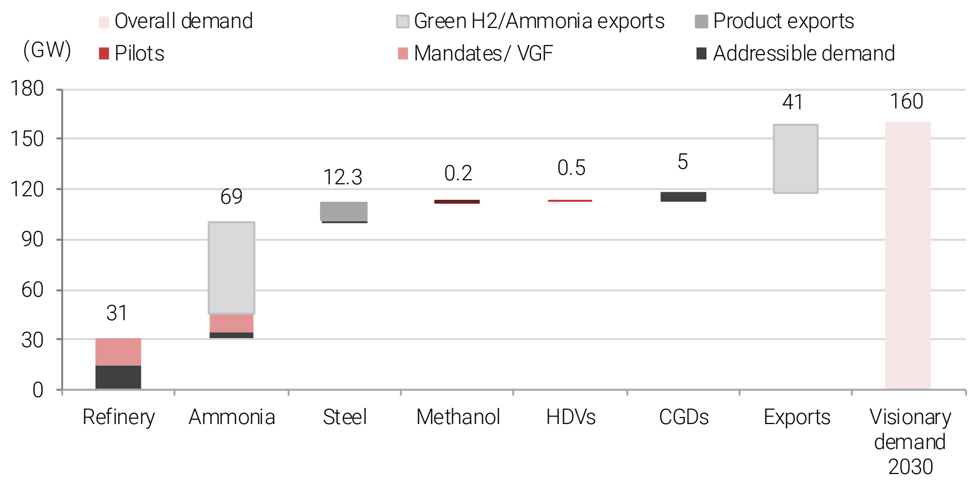
Domestic electrolyzer manufacturing capability important

For lower GH costs, apart from lower renewable power cost, the cost reduction of electrolyzers is critical. In addition, rising green H_2 demand will provide a large opportunity for creation of manufacturing capacity not only to meet Indian demand, but also for rising global electrolyzer demand. Niti Aayog had suggested setting up a minimum target of 25 GW of electrolyzer capacity in India.

Niti Aayog suggested setting up 160 GW of electrolyzer capacity by 2030

As we noted earlier for a no policy intervention scenario, Niti Aayog—RMI had estimated green H_2 demand of nearly 1.7 mt by 2030. This would require electrolyzer capacity of nearly 20 GW. In addition, based on different initiative-mandated blending and demand in new segments, it has estimated demand of nearly 45 GW. It has also suggested setting up an additional 95 GW capacity for the export of green H_2 and green ammonia, leading to overall capacity of 160 GW by 2030. For reaching this 160 GW electrolyzer target, Niti Aayog has estimated total investment of nearly US$ 250bn for electrolyzers and associated renewable capacity.

Exhibit 35: Niti Aayog's visionary 2030 electrolyzer capacity target for green H_2 production



Source: Niti Aayog, Kotak Institutional Equities

India refining: Switch to GH may pick up once cost becomes competitive

In refineries, hydrogen is primarily used for processes such as hydro-cracking (heavier hydrocarbon broken into smaller hydro-carbons), hydrogenation (hydrogen used to saturate organic molecules) and treatment processes such as hydro-treating or de-sulfurization. In recent years, with the focus on reducing sulfur content in petroleum fuels, the usage of hydrogen has been rising.

In India, with nearly 250 mmtpa refining capacity, it is estimated that refineries consume nearly 3 mmtpa of hydrogen annually or about nearly 46% of the current hydrogen consumption in the country. Though some hydrogen is produced during the refinery processes itself, bulk of hydrogen is produced using the SMR process. The gray hydrogen process to produce hydrogen leads to CO_2 emissions of about 10-12 ton per ton of hydrogen production. Thus, hydrogen production in the refining process itself, leads to about 30 mmt of CO_2 emissions annually.

Usage of GH in refining, apart from reducing emissions from this hard-to-abate industry, will enable early adoption and scaling up of GH usage in the country. In our view, to ensure a faster switch to green H_2 in refining, the government will likely mandate the GH consumption obligation (GHCO) for the sector.

Mandated adoption of GH will be capex intensive. On our estimates, for 1 mn tons of green H_2 usage (1/3rd of India's refining H_2 consumption), nearly 25 GW of renewable energy and 10-12 GW of electrolyzer capacity will need to be set up. The current capital costs of US$550-600 mn per GW of new solar capacity and US$500-600 mn per GW of electrolyzer capacity. Based on above assumptions, the **required capex to switch 1/3rd of India's refining capacity will require capex of nearly US$18-22 bn**. Similarly, if Reliance were to switch 25% of its refining capacity to green H_2 usage, it will require an upfront capex of US$4-4.5 bn, on our estimates.

Though upfront capex for green H_2 switch will be high, based on levelized cost, margin impact will be low

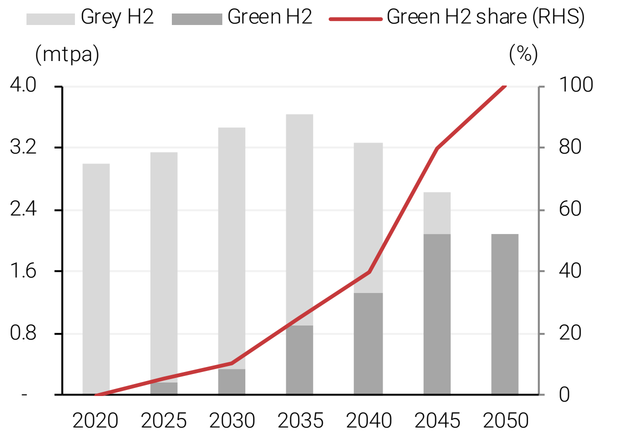
Exhibit 36: Likely impact on refining GRMs on GH usage (US$/bbl)

		2024	2026	2030	2035
Grey H2 cost	US$/kg	2.0	2.0	2.0	2.0
Green H2 (levelised)	US$/kg	5.0	4.0	3.0	2.0
Share of green H2	%	1	5	10	25
Incremental cost	(US$/ bbl)	0.05	0.2	0.2	—

Source: Kotak Institutional Equities estimates

Switch to green H_2 will likely be slow initially, but would likely be rapid beyond 2035

Exhibit 37: Refining—likely H_2 use and green H_2 share (mmt, %)



Source: Kotak Institutional Equities estimates

We also note that switching to green H_2, apart from reducing carbon emissions, do not provide any advantage to refiners. The new capex on green H_2, only makes existing gray H_2 facilities redundant. In the initial years, based on levelized costs, green H_2 is also more expensive versus gray H_2. However, as GH costs become competitive versus gray H_2 (likely by 2030-35) and if carbon emission penalties are imposed on gray H_2 usage, we think the switch to GH can accelerate.

We estimate that due to the increases in refining capacities and the increasing usage of H_2 to reduce the sulfur content in products, overall H_2 usage will pick up in the refining sector until 2035. We expect green H_2 usage to gradually pick up until 2035, mainly driven by mandates such as GHCO. However, beyond 2035, as green H_2 becomes cheaper than gray H_2, we expect GH conversion to accelerate.

India fertilizers: H_2 consumption will likely double, could entirely switch to GH in LT

The fertilizer industry is the largest user of H_2 in the country, with the current usage estimated at ~3.8 mmtpa in FY2023. Though ammonia-based urea production has the highest usage of ammonia (and H_2), it is also in other types of fertilizers as well. H_2 usage in fertilizer is expected to pick up substantially over the years. The per capita consumption itself is expected to increase from about 48/kg in FY2023 to ~70-75/kg by 2050. In addition, currently, India imports nearly 30% of the fertilizers it needs. As we noted earlier, the NGHM targets to replace all imports of ammonia-based fertilizers by domestic green ammonia-based fertilizers by 2034-35.

Similar to refinery, at current costs, GH is not competitive versus natural gas-based gray H_2 that is used to make most ammonia-based fertilizers in the country. According to Niti Aayog/RMI, even at relatively higher gas prices of US$12/mmbtu, green ammonia costs are higher than those produced by the SMR process. However, as GH/ammonia costs will likely become competitive by 2030. Even at the lower end of the gas prices of US$8/mmbtu, both green and gray ammonia will have similar cost levels at about US$400/ton of ammonia.

Ammonia-based fertilizers need large quantum of H_2

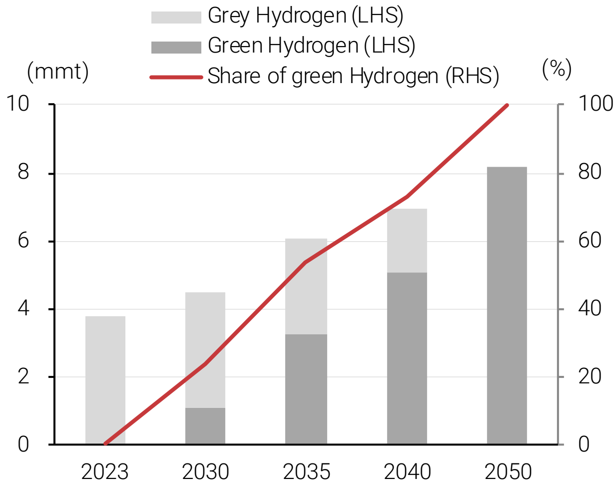
Exhibit 38: Estimate of H_2 required in fertilizer sector in 2023 (mmt)

Fertilizer	Kg NH3/t	Kg H2/t	production	(mmt)
Urea	570	103	28	2.9
DAP	230	41	4	0.2
Other CF	240	43	16	0.7
Total			**49**	**3.8**

Source: TERI, Kotak Institutional Equities estimates

We expect switch to green H_2 to scale up after 2030

Exhibit 39: Fertilizer—likely H_2 use/green H_2 share (mmt, %)



Source: Kotak Institutional Equities estimates

Fertilizer sector will likely have high usage of GH

Exhibit 40: Estimate of domestic fertilizer capacity, H_2 needs and GH share

		2023	2030	2035	2040	2050
Total consumption	mmt	67	73	81	89	105
Domestic production	mmt	49	57	78	89	105
Hydrogen requirement	mmt	3.8	4.5	6.1	7.0	8.2
Assumed mandate for existing plants	%	—	10	25	50	100
Green Hydrogen share *	mmt	—	1.1	3.3	5.1	8.2

Note:

(a) We assume all new capacity will be based on GH and mandates will be in place soon for switch of existing capacity to GH.

Source: Kotak Institutional Equities estimates

In our view, with the fertilizer industry controlled by the government and subsidy schemes in place, the implementation of mandates to switch to GH will likely be easier. Apart from new GH-based fertilizer plants, we expect the government to have a mandate of faster switching for the fertilizers segment (versus refining capacity).

Conversion to GH negative for LT gas demand outlook

We note that in the past several years, the fertilizer sector has been the largest consumer of gas in India. In recent years, due to reduced availability of domestic gas and the lower priority of the fertilizer sector (versus CGDs), domestic gas availability for the fertilizer sector has been declining. However, this has been offset by increased usage of imported LNG. In the past few years, as five new gas-based fertilizer plants have started, gas usage has further increased to about 54-55 mmscmd.

In addition, the fertilizer sector's gas demand has been historically price agnostic. Even if gas prices have been elevated, the fertilizer sector continues to consume gas, as 1) gas costs are fully reimbursed by central government subsidy and 2) in the case of lower domestic production, there will be increased imports of fertilizers.

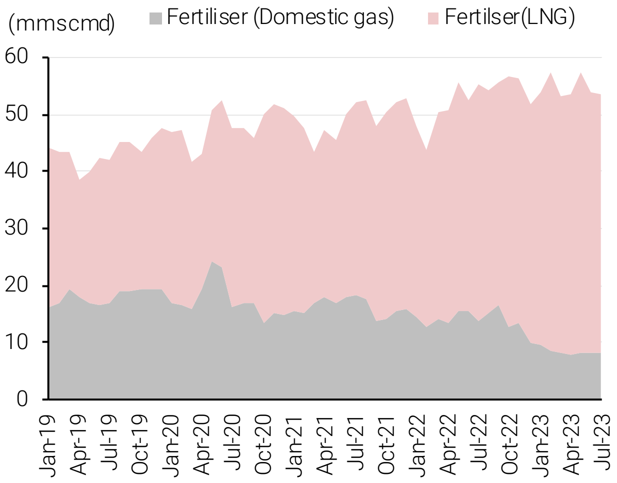
The refining sector has also been a large user of gas in the country for the production of hydrogen and other energy uses in refining. Though there is no APM allocation, refiners have been using domestic non-APM gas (such as HPHT gas) and imported LNG. However, unlike fertilizers, the refinery sector's gas usage is price elastic. When liquid fuel versus gas prices arbitrage is high (such as in 2020), gas usage in the refining sector was high; this declined when gas prices were high (such as in 2022). In recent months, gas usage in refining has been ~15-16 mmscmd.

Both fertilizer and refining sectors together account for nearly 40% of India's gas consumption. In our view, with the focus now on carbon abatement and on green ammonia-based fertilizers, any new gas-based fertilizer capacity is unlikely to be set up. As we mentioned earlier, NGHM mentions that the new capacity to substitute imports will be based on GH.

We also expect the government to soon announce mandates for increasing the usage of GH in both fertilizer and refining industries. The increased reliance on GH will curb natural gas usage in both the fertilizer and refining sectors. With GH costs likely to become competitive post-2030 and the pace of the transition to GH likely to get faster, gas consumption for both these key user segments can significantly decline.

Fertilizer sector has highest share of gas consumption in India; it would be under threat if GH usage picks up

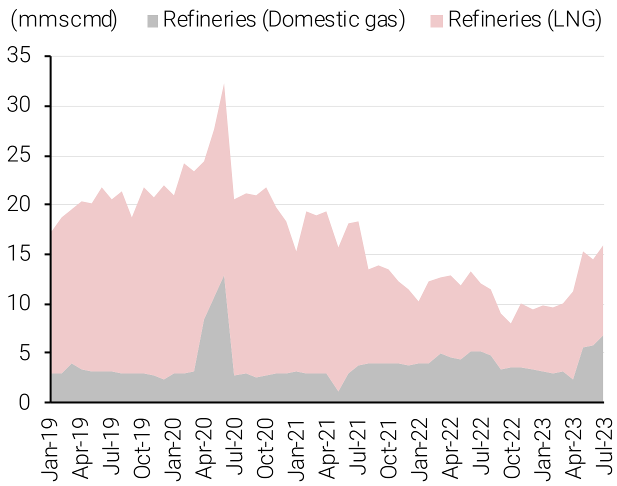
Exhibit 41: Fertilizers—gas consumption, January 2019 onward (mmscmd)



Source: PPAC, Kotak Institutional Equities

Gas usages in refining has been volatile depending on price arbitrage

Exhibit 42: Refineries—gas consumption, January 2019 onward (mmscmd)



Source: PPAC, Kotak Institutional Equities

4

India aims to be hydrogen hub

On Independence Day in August 2021, the Indian government initially announced the NGHM (notified in January 2023). With the government announcing several incentives, there has been a rush from Indian corporates to announce GH plans. So far, in our view, the progress has been relatively slow. However, with the government announcing incentives for both GH production and electrolyzer manufacturing, the activity should increase. Firm announcement of GH consumption obligations (GHCO) for hard-to-abate sectors, such as the fertilizer and refining sectors initially, and other industries in the next few years, could accelerate the investments in the GH chain, in our view.

The Indian Prime Minister on August 15, 2021, had first announced NGHM, with the aspiration of India becoming a global hub for GH production and exports. This was not only to help India become self-reliant in energy, but also to become a new inspiration for clean-energy transition.

Several policy measures to make India a H_2 hub

Exhibit 43: India's key policy announcements on GH

Aug-21	National Green Hydrogen Mission initially announced
Feb-22	New Green Hydrogen/Ammonia policy with incentives like ISTS charges waiver, banking of RE power
Jan-23	Cabinet approval for National Green Hydrogen Mission with initial outlay of Rs197 bn
Aug-23	Green hydrogen standard notified with emission threshold of 2 kg CO_2 equivalent per kg H2
pending	Green Hydrogen consumption obligations (GHCO) for end use sectors

Source: MNRE; Kotak Institutional Equities

Green H_2/green ammonia policy was a first step to NGHM

In February 2022, as a step toward NGHM, the government had notified a GH/green ammonia policy. This policy provided several incentives to encourage the production of GH and ammonia. The key measures included:

- Green hydrogen/ammonia manufacturers could purchase RE power from the power exchange or set up RE capacity themselves or through any other developer, anywhere.
- Open access to be granted within 15 days of receipt of application. Priority connectivity to the grid.
- Green H_2/ammonia producer could bank unconsumed RE power, up to 30 days, with DISCOMs.
- 25-year waiver on inter-state transmission (ISTS) charges for the projects commissioned before June 2025.
- Renewable purchase obligations (RPO) provide benefit to green H_2/ammonia producers.
- Green H_2/ammonia allowed to set up bunkers near ports for storage.

Few states such as Uttar Pradesh (UP), Rajasthan, Odisha and Gujarat have also announced policies in alignment with the Green Hydrogen Policy. Maharashtra and Gujarat have announced benefits such as concessional electricity and duty-reimbursements on production of GH and its derivatives.

NGHM targets at least 5 mmt green H_2 production capacity by 2030

After extensive consultation, NGHM was approved by the Union Cabinet in January 2023. NGHM aims to provide a comprehensive action plan for establishing a GH ecosystem in India and catalyzing a systemic response to the opportunities and challenges in scaling up GH production and utilization across multiple sectors.

The overarching objective of the mission is to make **India the global hub for production, use and export of GH and its derivatives**. This will contribute to India's aim to become *Aatmanirbhar* (self-reliant) through clean energy and serve as an inspiration for the global clean energy transition.

The NGHM will support replacement of fossil fuels and fossil fuel-based feedstocks, with green H_2 and its derivatives. This will include the replacement of H_2 produced from fossil fuel sources with green H_2 in ammonia production and petroleum refining, blending green H_2 in city gas distribution systems, production of steel with green H_2, and use of GH-derived synthetic fuels (including green ammonia and green methanol) to replace fossil fuels in various sectors, including mobility, shipping and aviation.

The mission will lead to significant decarbonization of the economy, reduced dependence on fossil fuel imports, and enable India to assume technology and market leadership in GH, electrolyzers and other enabling technologies for GH.

- Under NGHM, the government is targeting the setting up of **at least 5 mmtpa GH capacity by 2030**. With the growth of export markets and international partnership, the GH capacity could be scaled up to reach 10 mmt.
- To produce 5 mmtpa green H_2, **60-100 GW of electrolyzer capacity** and **125 GW of renewable power capacity** and associated transmission network capacity to be set up.
- NGHM envisages total investment of over Rs8 tn, which could result in the creation of 600,000 jobs. This would also lead to the abatement of nearly 50mmt of annual GHG emissions and cumulative reduction in fossil fuel imports by over Rs1 tn.

With at least 5 mmtpa green H_2 production, over 50 mmtpa of CO_2 emissions likely to be averted

Exhibit 44: Expected outcome of NGHM

Source: Ministry of Renewable and New Energy; Kotak Institutional Equities

NGHM would support the replacement of fossil fuels/feedstocks with renewable fuels/feedstocks based on GH. These will include:

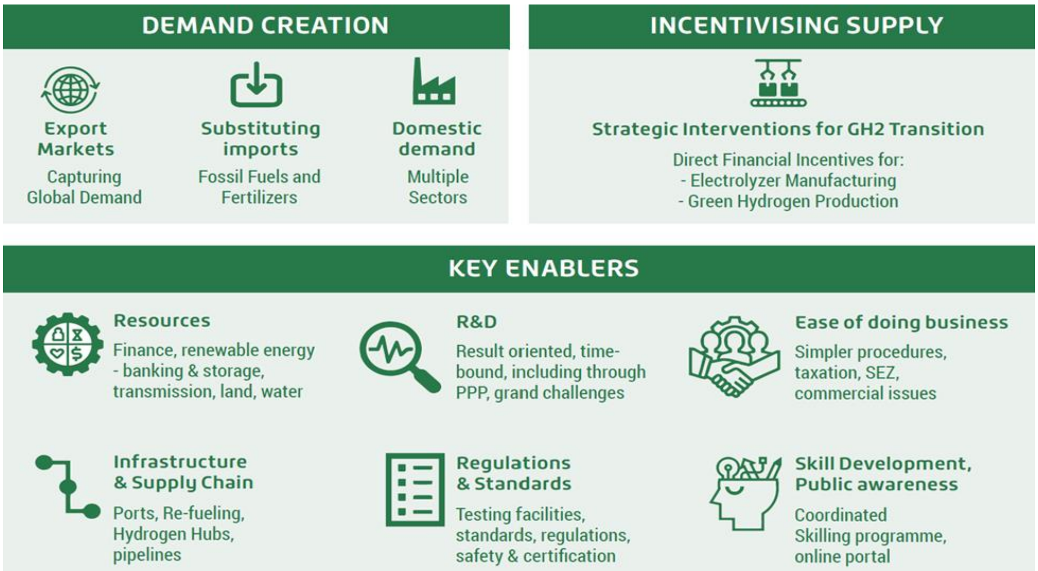
- Replace gray H_2 used in ammonia production and petroleum refining with green H_2
- Blend green H_2 in city gas distribution systems
- Steel production with green H_2 to make green steel
- Production of green H_2-derived synthetic fuels (including green ammonia and green methanol) to replace fossil fuels in various sectors, including mobility, shipping and aviation

The mission proposes interventions to boost domestic manufacturing. NGHM would take steps to enable cost reduction in input renewable energy, electrolyzers, supply and treatment of water, storage and distribution, conversion of H_2 to suitable derivatives, and enabling infrastructure.

It also proposes to extend various facilitative policy provisions for transmission, connectivity, banking, open access and energy storage for green H_2 production projects.

NGHM is proposed to be implemented in phases. Initial focus would be on sectors that are already using H_2 in some form and are hard to abate such as fertilizer and refining.

Exhibit 45: Key components of NGHM



Source: Kotak Institutional Equities

Phase 1 (2022-23 to 2025-26): Focus on demand creation and enabling adequate supply

- In the first phase, the mission's focus would be on creating demand while enabling adequate supply by increasing the domestic electrolyzer manufacturing capacity.
- **Refineries, fertilizers and city gas sectors will be the key target sectors**.
- It will also lay the foundation for future energy transitions in other hard-to-abate sectors (steel, long-haul heavy-duty mobility and shipping) by creating the required R&D impetus.

Phase 2 (2026-27 to 2029-30): Accelerate production growth with cost competitiveness

- In the second phase, green H_2 costs are expected to become competitive with fossil-fuel based alternatives in the refinery and fertilizer sectors. This would allow for accelerated production growth.
- Commercial scale green H_2-based projects in the steel, mobility and shipping sectors will be explored. The progress will depend on the evolution of costs and market demand.
- Pilot projects will be undertaken in other potential sectors such as railways and aviation.
- Phase 2 is expected to enhance penetration across potential sectors to drive deep decarbonization of the economy.

SIGHT program to provide strategic interventions/fiscal incentives of ~Rs175 bn

NHGM's strategy also includes a comprehensive incentive program to facilitate the growth of the green H_2 value chain. This program is called Strategic Interventions for Green Hydrogen Transition (SIGHT).

At the initial stage, the government has an outlay of Rs175 bn for two distinct financial inventive mechanisms for 1) domestic manufacturing of electrolyzers at an outlay of Rs44 bn and 2) production of GH, with an outlay of Rs131 bn. Solar Energy Corporation of India (SECI) would be the implementing agency responsible for the scheme's execution.

In addition to SIGHT, the government has set a further outlay of Rs22 bn for other activities such as pilot projects, R&D and other mission components.

Exhibit 46: NGHM implementation timelines

	Facilitate	Green Fertilizers	SIGHT	Pilots & Hubs	Regulations & Standards	R&D
2022-23			Consultation and market review	Roadmap for key sectors	Procedure for regulatory approval of pilots	Formulation of R&D Roadmap
2023-24	Notification of targets	Bids notification / Capacity award	Notification of Incentive Schemes	Call for Proposals	Adoption of relevant international standards	Call for Proposals
2024-25	Peparatory steps for implementation	Construction		Phase 1 implementation	Continuous Review and Monitoring	Phase 1 implementation
2025-26	Implementation	Green Fertilizer production	Implementation of incentives	Calls for proposals		Calls for proposals
2026-27						
2027-28						
2028-29				Phase 2 Implementation		Phase 2 Implementation
2029-30						

Source: Ministry of New and Renewable Energy, Kotak Institutional Equities

Electrolyzer manufacturing incentive scheme

Key objectives of this scheme are 1) achieving lower levelized cost of production, 2) maximizing the indigenous manufacturing capacity, 3) ensuring globally competitive performance/quality of products, 4) progressively enhancing domestic value addition and 5) supporting established and promising technologies.

This scheme has an initial outlay of Rs44 bn over FY2026-30. This will be provided in the form of incentives per kilowatt (Rs per kW) of manufacturing capacity for the first five years of the manufacturing facility. The base incentive will start with Rs4,440/kW in the first year and will gradually taper down annually.

The **target capacity for the first phase is set at 1,500 MW**, with the maximum capacity allotted to a single bidder fixed at 300 MW and minimum capacity bid of 100 MW. The scheme aims to progressively indigenize the electrolyzer value chain and bidders would be required to demonstrate a minimum level of local value addition (LVA) annually, according to Exhibit 48.

Exhibit 47: Base incentive available each year for electrolyzer production under the scheme (Rs/kW)

Year of sales	Base incentive (Rs/kW)
Year 1	4,440
Year 2	3,700
Year 3	2,960
Year 4	2,220
Year 5	1,480

Source: MNRE, Kotak Institutional Equities

Exhibit 48: Minimum local value addition (LVA) for each year of production for electrolyzers

	Minimum LVA for electrolysers	
Year of production	Alkaline	PEM/AEM/ Solid Oxide
1st	40%	30%
2nd	50%	40%
3rd	60%	50%
4th	70%	60%
5th	80%	70%

Note:

LVA = [{(Sale value of electrolyzer) – (value of imports)} / (Sale value of electrolyzer)]

Source: MNRE, Kotak Institutional Equities

Incentive scheme for GH production

The key objectives of this scheme are to 1) maximize green H_2 and derivatives production, 2) enhance cost-competitiveness of green H_2/derivatives versus fossil fuels and 3) encourage large scale utilization of green H_2/derivatives.

For this scheme, the government has set an outlay of ~Rs131 bn for FY2026-30. The incentive will be provided for the first three years of green H_2 production on per kg basis. The incentives are capped at Rs50/40/30 per kg in the first/second/third years.

The first phase would have total bidding capacity of 450 ktpa. Of this, 410 ktpa is under technology agnostic pathway, whereas 40 ktpa is to be based on the biomass pathway. The maximum allocated capacity per player in the technology agnostic pathway is fixed at 90 ktpa and minimum at 10 ktpa, whereas the maximum allocated capacity per player under biomass-based pathways would be 4 ktpa, with the minimum at 500 tpa.

There are two modes of participation in the scheme. In mode 1, interested parties can bid based on least incentives demanded over a three-year period, through a competitive selection process. Mode 2 involves implementing agency (SECI) aggregating demand and initiating a competitive bidding system for procuring GH and its derivatives at the most economical cost.

In the cases where the end-product is a derivative of GH such as green ammonia, the incentive would be made available based on the amount of GH (in kg) utilized to produce the given amount of the derivative. For green ammonia, the equivalence factor would be 0.1765 kg GH per kg of green ammonia.

Exhibit 49: Year-wise incentive cap for green H_2 production (Rs/kg)

Year	Incentive cap (Rs/kg)
1st	50
2nd	40
3rd	30

Source: MNRE, Kotak Institutional Equities

Exhibit 50: Green H_2 capacity to be auctioned in tranche 1 (tpa)

Pathway	Capacity (tpa)
Technology agnostic	410,000
Bio-mass based	40,000
Total	**450,000**

Source: MNRE, Kotak Institutional Equities

GH Consumption Obligations (GHCO) may be announced soon

In our view, to achieve the rapid development of a green H_2 ecosystem, apart from fiscal incentives such as those given in SIGHT, there will also be a need to have compulsory GH consumption obligations (GHCO) for sectors that are already producing and consuming H_2, albeit gray H_2 and not green H_2.

We understand that earlier drafts of NHGM had contemplated having consumption obligations for current large users and hard-to-abate sectors such as oil refining and fertilizers. According to media reports, for oil refining the use of GH was to rise from 3% in 2025 to 30% by 2035. For the fertilizer sector, it was to start at 15% in 2025 and rise to 70% by 2035. For city gas distributors (CGDs), it was envisaged to start from 5% in 2025 to 15% by 2035.

In the final version of NGHM, obligation for each sector is not specified. However, the NGHM says that in order to create bulk demand and scale up green H_2 production, the **Indian government will specify a minimum share of consumption of green H_2** (or its derivatives such as green ammonia or methanol) by consumers as energy feedstock. **The year-wise trajectory of such a minimum share of consumption will be decided by an Empowered Group** (headed by the Cabinet Secretary), taking into account the availability of resources for green H_2 production, relative costs and other factors.

Ammonia-based fertilizer imports to be replaced by domestic green ammonia-based fertilizers

According to NHGM, in FY2021, India imported ~10 mmt of urea, 5 mmt of di-ammonium phosphate (DAP) and 3 mmt of ammonia. These imports were of nearly US$6bn. With the expected reduction in green H_2 costs, there will be an economic rationale for producing these in India using GH.

As part of the mission, the Ministry of New and Renewable Energy will be formulating model bidding guidelines for the procurement of green H_2-based ammonia. Two plants each for production of urea and DAP, based on green H_2, are initially targeted to be set up through competitive bidding. By 2034-35, all imports of ammonia-based fertilizers will be replaced by domestic green ammonia-based fertilizers.

Pilot projects for key potential demand sectors

For other hard-to-abate sectors, MGHM has proposed pilot projects for using green H_2/derivatives to replace fossil fuels. The sectors include steel, long-range heavy-duty mobility, energy storage and shipping. Pilot projects will help identify operational issues and gaps in terms of current technology readiness, regulations, implementation methodologies, infrastructure and supply chains. These will serve as inputs for future scaling commercial deployment.

- **Green steel:** NGHM will support efforts to enhance low-carbon steel production capacity. Considering the higher cost of green H_2 at present, steel plants can begin by blending a small green H_2 percentage initially. This can be progressively increased as cost economics improves and technology advances.
- **Transport**: NGHM will support the deployment of FCEV buses and trucks in phases on pilot basis. Financial assistance will be provided to close the viability gap due to the relatively higher capital cost of FCEVs in the initial years.
- **Shipping:** Maritime transport and ports have significant potential for decarbonization by use of green H_2 or its derivatives (green ammonia/methanol) propulsion fuel and other operations. The Shipping Corporation of India (SCI) **will retrofit at least two ships to run on green H_2/derivatives by 2027**. **Oil PSUs will need to charter at least one ship each** powered by green H_2/derivatives by 2027. Thereafter, they will be required to add at least one such ship each year.

Indian government has recently notified the GH standard

In August 2023, the government has notified the green H_2 standard that defines emission norms for H_2 to be termed green. The standards require well-to-gate emissions (including water treatment, electrolysis, gas purification, drying and compression of H_2) to stay below **two kg of CO_2 equivalent per kg of H_2** produced as a 12-month average.

This standard is applicable to H_2 produced by water electrolysis or by biomass processing, excluding H_2 produced through microbial processes. The Bureau of Energy Efficiency (BEE) would be the nodal authority to accredit agencies for monitoring, verification and certification of GH production projects.

5

Green hydrogen initiatives by corporates

Over the past few years, with the rising competitiveness of GH and the government's push, Indian corporates have also announced their H_2 plans. As such it is early stage and as most companies are at learning stage, progress is slow. In our view, as GH becomes even more competitive and as the government mandates its usage and provides incentives, the developments will likely pick up.

Reliance Industries

Among Indian corporates, Reliance has one of the most ambitious plans of transitioning to new energy. In 2021, it had announced plans to set up a green energy giga complex. This complex will have giga scale factories for photo-voltaic panels, GH, fuel cell system, energy storage and power electronics.

Reliance is already one of the largest producers of gray H_2. It now is working to create a GH ecosystem. RIL collaborated with Denmark's Stiesdal to reduce costs, commercialize their pressurized alkaline electrolyzer technology and to manufacture H_2 electrolyzers in India. It is also in discussion with other leading electrolyzer technology players.

After proving cost and performance targets, RIL aims to progressively transition from gray to GH by 2025. RIL is looking to significantly reduce the H_2 production costs. In 2021, Reliance had said that India has the potential to become the first country in the world to produce green H_2 at a cost of less than $1 per kg in the next decade.

Reliance is progressively building a GH ecosystem. It is targeting to establish a 20 GW solar PV capacity by 2025. This will be used for its need for RTC power and intermittent energy for GH production. It plans to gradually transition its own captive requirements and start production of green ammonia and green methanol for domestic and international markets.

To develop and demonstrate the end-use of H_2, Reliance has also demonstrated heavy-duty vehicles with H_2 as fuel. In early 2023, it had demonstrated India's first H_2 combustion engine technology. Recently, it also unveiled a fuel cell bus in collaboration with Bharat Benz.

Reliance launched India's first H2-ICE truck with Ashok Leyland

Exhibit 51: Hydrogen internal combustion engine (H2ICE) truck

Source: Company, Kotak Institutional Equities

Reliance also launched FCEV bus with Bharat Benz

Exhibit 52: Hydrogen fuel cell electric (H2FCEV) bus

Source: Company, Kotak Institutional Equities

Adani New Industries Limited (ANIL)

Adani Enterprise Limited (AEL) has incorporated Adani New Industries Ltd (ANIL) to act as a holding company of the end-to-end supply chain of frontier energy and technologies, addressing the need of India's long-term energy security. This initiative encompasses the entire supply and value chain. ANIL intends to have a fully integrated GH ecosystem to access low-cost renewable power, produce low-cost GH at scale and manufacture downstream products.

It intends to invest **up to US$50 bn over 10 years in the GH ecosystem and produce up to 3 MMTPA of GH**. It will develop Mundra as a world-class GH hub. ANIL intends to establish an integrated green platform, comprising three key segments.

- **Manufacture of supply chain products**: It will manufacture essential components for renewable energy generation (polysilicon, ingots, wafers, solar cells with modules, wind turbines, generators, electrolyzers, fuel cells and related products). It will have a 4 GW solar manufacturing capacity, including existing 2 GW and further expansion of 2 GW. It aims to achieve a manufacturing capacity of 10 GW.
- **GH production:** Focus will be on integrated renewable energy generation, utilizing capacities in solar and wind energy. It is targeting to produce up to 3 mmpta GH.
- **Downstream products**: This segment will concentrate on the production of significant downstream products, including ammonia, urea, methanol/ethanol and other key projects.

In the initial phase, the company is developing GH production capacity of up to 1 MMTPA in Gujarat in phases. The first GH production is likely to commence by FY2027.

The company intends to develop electrolyzers in-house based on the latest technologies. With technology development and economies of scale, it expects declining costs of electrolyzers. **It intends to reduce the cost of GH to less than US$2 per kg.**

Recently, Adani Group announced a 50:50 joint venture (JV) with Kowa Holdings, Singapore, for the sales and marketing of green ammonia, GH and its derivatives. The JV will concentrate on the marketing of products in Japan, Taiwan and Hawaii.

NTPC

NTPC is targeting an aggressive approach to expanding renewable energy, including GH. It is aiming for 45-50% of its capacity to come from non-fossil fuels by 2030 and has **a target to achieve 60 GW of renewable energy capacity by 2032** and be a major player in green H_2 technology and energy storage domain. It currently has over 3+ GW of installed capacity and 20+ GW capacity in the pipeline.

It has set separate subsidiaries NTPC Green Energy Limited (NGEL) and NTPC Renewable Energy Limited (NREL) to drive energy transition initiatives.

NTPC aims to reach a leadership position in GH technologies by FY2030 and has set a **target of 5 GW electrolyzer capacity for GH by FY2030**. NTPC conducts pilots on GH and alternate chemicals to drive the energy transition in various sectors. It has allocated a total budget of Rs3.5 bn for green demonstration projects, including GH.

- NTPC, in collaboration with Gujarat Gas, has successfully commissioned **a H_2 blending project in piped natural gas** (PNG) at the NTPC Kawas Township in Surat. Regulator PNGRB has initially approved 5% vol./vol. blending; this can be later scaled up to 20%.
- NTPC is setting up **GH mobility projects in Ladakh and Delhi NCR**, with five GH-based fuel cell buses at each place. Trials of buses in Ladakh have recently commenced.
- It is also working with the Indian Army to set up GH-based microgrids.
- It has awarded the contract for up to 600 MW alkaline electrolyzers to Hild Electric. It is also in the finalization stage of sourcing 400 MW PEM electrolyzers.
- It is undertaking other projects for GH such as the development of a seawater electrolyzer, metal hydride-based H_2 compression and storage.
- NTPC has also conceptualized **a GH hub near Vishakhapatnam**. This will include manufacturing of H_2-related equipment, production and exports of green H_2. The MoU with the Andhra Pradesh government has been signed.
- It is also working on multiple avenues of production of various chemicals and alternate fuels such as green ammonia (1,185 TPD at various locations), urea and green methanol (270 TPD at multiple locations).

Exhibit 53: NTPC's planned green methanol projects

Location	ton/day
Vindhaychal, MP	10
GACL, Dahej	25
GNAL, Dahej	25
Vadodara	25
Gajraula, UP	185

Source: Company, Kotak Institutional Equities

Exhibit 54: NTPC's planned green ammonia projects

Location	ton/day
Dahej	35
Nangal, Punjab	50
Gajraula, UP	100
Bhuj, Gujarat	1000

Source: Company, Kotak Institutional Equities

Indian Oil

Among oil PSUs, IOC seems to have more aggressive plans to invest in energy transition. With a net-zero target of 2046, **it has talked of a Rs 2 tn (US$24 bn) energy transition**. It is in the process to consolidate all transition efforts such as bio-fuels, renewables, GH and CCUS efforts under one umbrella. Its target includes setting up a portfolio of renewable energy and bio-fuels. It has set targets of:

- 5.5 GW RE generation capacity and 0.7 mmt biofuels production by 2025
- **31 GW RE capacity and 4 mmt biofuels (including biogas) production by 2030**
- 200 GW RE capacity, 7 mmt biofuels and 9 mmt biogas by 2050

It is currently developing a 7-10 ktpa (~85 MW) GH capacity at its Panipat refinery, and has plans to set up GH capacities at each refinery. It has formed JVs with ReNew and L&T to develop (including construction) GH production assets, including associated renewable assets. In another JV finalized with L&T, it will look to manufacture and sell electrolyzers.

IOC has undertaken a pre-feasibility study of the fuel cell technology for heavy-duty applications. This will generate data pertaining to fuel cell performance, efficiency and operational reliability of H_2 refueling infrastructure. To establish the efficacy, efficiency and sustainability of the production process and fuel cell technology, it has ordered 15 fuel-cell buses based on PEM technology. The first set of buses have been recently deployed in Delhi. Two prototype fuel cell buses are also being tested in Vadodara.

The technology will be demonstrated in **15 fuel cell buses** for establishing the efficacy, efficiency and sustainability of the production process and fuel cell technology.

ONGC

With a net-zero target by 2038, ONGC is currently focused on identifying opportunities in the renewable energy and low-carbon sector. It has recently committed **to spend nearly Rs1 tn (US$12 bn) on multiple green initiatives**. It is targeting to scale up the renewable energy portfolio to **10 GW by 2030**. In addition, it is exploring collaborations, with leading players on various low-carbon energy opportunities, including renewables, GH, green ammonia and other derivatives of GH.

It has entered a partnership with the Rajasthan government **to establish a 5 GW solar capacity along with downstream GH and green ammonia capacity**.

ONGC has established an MoU with Equinor. This partnership entails the joint exploration of opportunities in CCUS and the development of offshore wind and/or solar/solar hybrid projects within India and collaborating on advancing technologies related to green and blue H_2 and ammonia production.

It also has a collaborative agreement with the Centre for High Technology (CHT) to develop affordable technology for GH production through the indigenous membraneless electrolyzer and its storage using lower-cost materials having a minimal environmental impact.

L&T

As part of its ESG commitments, L&T has pledged to achieve water neutrality by 2035 and carbon neutrality by 2040. L&T's Green Energy business, with its focus on GH and its derivatives, will be an integral part of the company's Clean Fuel Adoption Policy.

L&T is developing a GH project installation/EPC capability and setting up manufacturing facilities for electrolyzers and battery cells to ride the global green transition wave. It is also exploring technical collaborations with global players.

- In a step toward setting up a GW scale manufacturing facility in India, it entered **into a technology license agreement with McPhy Energy**, a France-based leading pressurized alkaline electrolyzer technology and manufacturing company.
- L&T has also entered into **an MoU with Norway-based H2Carrier (H2C)** to develop floating green ammonia projects for industrial-scale applications.
- L&T has also signed a collaboration agreement with IIT Bombay for the development of a GH value chain.

During FY2023, L&T commissioned a pilot plant for captive consumption of GH at its Hazira facility. The plant is designed for an electrolyzer capacity of 800 kW, comprising both alkaline and PEM technologies. The plant is powered by a rooftop solar plant of 990 kW peak DC capacity and a 500 kWh Battery Energy Storage System (BESS).

The alkaline electrolyzer of 380 kW capacity produces 45 kg per day (15 tpa capacity) of high-purity H_2 (99.99%). This H_2 is blended with natural gas for captive consumption in the existing fabrication shops in Hazira. A 400 kW PEM electrolyzer will be added as part of future expansion, doubling the H_2 production capacity of the plant to 30 TPA.

Greenko Group

Greenko is one of India's leading renewable energy companies, with an installed capacity of 7.5 GWdc across 15 states in India. The company also delivers low-cost round-the-clock renewable energy (RE-RTC) through its ~100 Giga Watt Hours daily storage capacity intelligent renewable energy storage platform (IRESP).

Greenko is setting up a multiphase green ammonia production and export facility at Kakinada, adding up to 1 mmtpa of green ammonia capacity by 2027. The first phase produces green ammonia based on an electrolyzer powered by RTC renewable electricity produced by 2.5 GW of renewable assets in India and reinforced by their Pinnapuram IRESP. Greenko has signed an MoU with Uniper to engage in exclusive negotiations for ~250ktpa green ammonia offtake to the EU from its project in Kakinada.

It has recently placed an order for a 140 MW (28*5 MW units) high-pressure alkaline electrolyzer on John Cockerill (Belgium) for use in the development of a green ammonia plant to be commissioned by June 2024 at Una, Himachal Pradesh. The 300 ton/day plant—jointly developed by Greenko ZeroC (GZC), a subsidiary of Greenko Group and John Cockerill—will be the largest green ammonia plant in India to date.

Greenko and John Cockerill had earlier signed a strategic partnership agreement to work on projects that will advance the creation of GH and are jointly developing a 2 GW electrolyzer manufacturing plant in Kakinada, Andhra Pradesh.

In July 2022, Greenko ZeroC had established a strategic partnership with ONGC for the production of green ammonia and related derivatives. The companies aim to form a JV to set up a 1.3 GW GH plant to produce 1 mmtpa of green ammonia.

ReNew Power

ReNew Power aims to develop several GH projects in India and overseas.

ReNew Power has entered a **JV with L&T and IOCL** to develop GH projects in India and supply GH on an industrial scale.

ReNew Power has also signed a framework agreement with the Government of Egypt to set up a GH plant in the Suez Canal Economic Zone, **with an investment of US$8 bn and targeted 220 kta GH capacity**. The project is to be implemented in phases. Firstly, there will be a pilot phase to product 20ktpa of GH along with its derivatives by 2026 (using a 150 MW electrolyzer and 570 MW renewable energy). Later, the capacity will be ramped up further by 200 ktpa (using a 1.5 GW electrolyzer capacity and ~5.7 GW renewable energy) to 220 ktpa of GH. The final investment decision (FID) for the project is expected in the next 6-12 months.

Avaada Energy

Avaada is an upcoming integrated green energy platform, with interests across solar manufacturing, production of GH and its derivatives, green fuels, renewable power generation, and electrolyzer manufacturing. The company currently operates an RE portfolio of ~4 GW and ~7 GW under different stages of implementation.

Avaada has signed several agreements/MOUs to develop GH or derivative products.

- Avaada has signed an MoU with the Rajasthan government for a 1 mmtpa green ammonia facility with an envisaged investment of Rs400 bn.
- It has also signed an MoU with Tata Steel SEZ to establish a 0.5mtpa GH/ammonia production facility at the Gopalpur Industrial Park in Odisha.
- Avaada also intends to get into the manufacturing of electrolyzers and is in talks with a few foreign companies.

Overall, Avaada intends to invest US$5 bn in the green ammonia business. Recently, Avaada Energy raised ~US$1 bn from Brookfield to fund its GH and green ammonia ventures in India.

ACME Clean Energy

ACME has solar power projects across 12 states, with built and operated portfolio of 5 GWp and 10 GWp, respectively, under construction. The company envisions to become a leading green energy provider in the world by 2032 and producing 10 mn tons/year of green ammonia and H_2.

- In 2021, ACME set up a pilot GH (314 tpa) and green ammonia plant in Bikaner, Rajasthan. The company has also announced plans to build a GH and ammonia plant in Karnataka, Odisha and Tamil Nadu.
- ACME Clean Energy has also signed an MoU with Tata Steel SEZ to set up a 1.3 mmtpa green ammonia production facility, with an investment of Rs270 bn at the Gopalpur Industrial Park in Odisha. The green ammonia produced at this facility will be exported to markets in the West and East from the existing Gopalpur Port facilities. ACME Group has also signed a preliminary agreement with Japan's IHI to invest in this project.
- It has signed an MoU with Indraprastha gas (IGL) to jointly explore potential business opportunities of GH.
- ACME Group is implementing a green ammonia project at SEC in Duqm, Oman. In the first phase, ~100ktpa of green ammonia is expected to be produced, which will be subsequently ramped up to 1.2mtpa. The project will be powered by a 5.5 GWp solar PV plant and will have 3.5 GW electrolyser capacity. Recently, ACME Group has entered a tie-up for a Rs30 bn loan from Rural Electrification Corporation (REC) for its GH and ammonia project in Oman.

BPCL

BPCL has the ambition to add 1 GW in renewable energy capacity by 2025 and increase it to 10 GW by 2040. According to BPCL, the possibility of integrating H_2 with the existing gas infrastructure offers immense potential. However, there are challenges in transportation and storage currently.

Compared with IOC, so far, BPCL has not announced major plans for GH yet. It is currently implementing **a 20 MW GH plant at its Bina refinery**. To scale up its indigenous alkaline electrolysis technology for GH production, BPCL has signed a memorandum of agreement (MOA) with Bhabha Atomic Research Centre (BARC) in May 2023.

HPCL

Similar to BPCL, so far, HPCL has not made any major forays in GH, though it was the first OMC to place an order for an electrolyzer to produce GH. A **2.6 MW electrolyzer to produce 370 tpa GH at Vizag refinery** is in advanced stages of completion. HPCL is undertaking R&D on battery and electrolyzer technology to produce GH.

GAIL

GAIL has set a target to reach net-zero emissions by 2040. Apart from reducing scope 1 and scope 2 emissions by 100%, it is targeting to reduce scope 3 emissions by 35% by 2040. However, so far, its forays in GH are limited and are at a pilot scale.

In line with the NGHM, GAIL has started a pilot project to establish the techno-commercial feasibility of blending H_2 in CGD networks. The project is being done in collaboration with EIL and IIT Kanpur. GAIL is blending 5% H_2 (by volume) and blended H_2 is being supplied to Avantika Gas's Indore CGD network. It is also implementing a phased approach to blend GH with natural gas in gas turbines for power generation to reduce CO_2 emissions.

It is also setting up a 10 MW PEM-based GH plant at Vijaipur in Madhya Pradesh.

Oil India

Oil India commissioned a 10 kg/day GH in India at Jorhat, Assam. The plant is based on the AEM technology and produces 99.999% pure H_2. According to Oil India, AEM has benefits of both the alkaline and PEM technologies.

Oil India is also progressing on a study in collaboration with IIT Guwahati, with an objective to assess the impact of H_2-blended natural gas on existing facilities.

Indraprastha Gas

IGL is exploring the setting up of a GH generation plant for blending with natural gas. It has carried out a feasibility study and is further carrying out an assessment by a subject matter expert.

IGL and ACME Group have signed an initial pact to jointly explore potential business opportunities in GH. They will work together to explore the opportunity of setting up H_2 generation plants, including setting up electrolyzers to blend GH in IGL's CGD network.

Thermax

Thermax has partnered and signed an MoU with Fortescue Future Industries (FFI), an Australia-based green energy and green technology company, to explore opportunities to jointly develop fully integrated GH projects for commercial and industrial customers in India. Thermax and FFI would collaborate in the development of new manufacturing facilities in India and prospects for exports of electrolyzers and subsystems. Thermax is also working on developing a technology for producing GH from biomass.

JSW Energy

In its pursuit to transition into an energy products and services company, JSW Energy is setting up a 1 GW solar PV manufacturing capacity by 2025. It is now also integrating backward to add a 1 GW solar module manufacturing capacity and integrating forward to produce GH.

It will set up **India's largest commercial scale GH project, so far, with a capacity of 3,800 tpa**. JSWE expects to commission the project within 18-24 months (or by FY2025). The GH will be used to produce green steel at JSW Steel.

Torrent Power

Torrent Power is working on a pilot project for blending GH with natural gas in its city gas distribution (CGD) network. The pilot project based on an alkaline electrolyzer will blend 2.5% GH into the CGD network in Gorakhpur, Uttar Pradesh, and is expected to be completed in ~6 months.

A1

Annexures 1: H_2 fundamentals

Hydrogen (H_2) is the universe's most abundant material. With a single proton orbited by a single electron, it is also the simplest and lightest element in the universe. One cubic meter of H_2 weighs just 89 grams.

However, it is rarely found unbounded and in pure form in nature. Much of H_2 is found in water, which makes up nearly 75% of the earth. Nearly 60% of atoms in the human body are also H_2. It is also present alongside most organic compounds such as food and fuels made from organic matter. It is also estimated to make up more than 30% of the mass of the sun.

The hydrogen atom also binds itself with another hydrogen atom, which makes the hydrogen molecule; this is the lightest molecule. The hydrogen molecule moves up fast in the atmosphere and can quickly attain escape velocity to go beyond the earth's atmosphere into space. This means that there is no H_2 in the atmosphere. Unlike natural gas, which when released into the atmosphere has a large impact on the greenhouse effect, H_2's escape into space would unlikely lead to such concerns.

H_2 needs to be extracted from other sources such as water (by electrolysis) or from other hydrocarbons (steam methane reforming or pyrolysis).

High specific energy, but low energy density

Exhibit 55 compares specific energy (energy by weight) and volumetric energy density. At 142 MJ per kg, H_2 has the highest specific energy compared with other conventional fuel (3X of gasoline, 3.3X of diesel). Exhibit 56 shows that for each 1,000 kWh of energy compared with 25 kg of H_2, a much higher quantity of other conventional fuels are needed.

However, being the lightest molecule, in terms of energy density, H_2 is much behind other conventional fuels. For similar energy content, a much larger volume of H_2 needs to be carried. For carrying a meaningful quantity of energy, either H_2 needs to be compressed at high pressure or liquified. The boiling point of H_2, at negative 253°C (negative 423°Fahrenheit, 20 Kelvin), is nearly 90°C below LNG. This requires highly specialized cryogenic handling. This makes ammonia and synthetic fuels more attractive for long-distance travels such as in aviation and shipping.

H_2 has ~3X energy per kg versus gasoline, but for same energy, H_2 needs 3.5X-4X volume versus gasoline/diesel

Exhibit 55: Specific energy/energy density comparison, HHV (MJ/kg, MJ/liter)

	Specific Energy		Energy Density
	kWh/kg	MJ/kg	MJ/liter
Hydrogen			0.01 (1 bar)
Hydrogen	39.4	**142.0**	7.10 (1,000 bar)
Hydrogen			10 (liquid)
Methanol	5.6	20.0	15.9
Ammonia	6.3	22.5	15.6
Gasoline	13.1	47.3	35.0
Diesel	12.4	44.8	40.4
Heavy fuel oil	11.8	42.4	40.7
Biodiesel	11.7	42.2	33.0
Natural gas	14.4	52.0	0.04
LNG	14.4	52.0	22.2
Li-Ion batteries	0.28	1.0	2.8

Note:

(a) MJ = Mega Joule

Source: Kotak Institutional Equities estimates

With similar engine efficiency, per kg of H_2 will give over 4X distance versus per liter of petrol

Exhibit 56: Required quantity of fuels per 1,000 kWh of energy content (kg, liter, mmbtu or scm)

	per 1000 kWh	
Hydrogen	25	kg
Ammonia	160	kg
Gasoline	103	liter
Diesel	89	liter
Heavy fuel oil	88	liter
Natural gas	3.4	mmbtu
Natural gas	92	scm
CNG	69	kg

Note:

(a) 1 kWh = 3.6 MJ

Source: Kotak Institutional Equities estimates

H_2 leaves no carbon footprint

Exhibit 57: H_2 versus fossil fuel—carbon/H_2 content and CO_2 emission comparison

	Carbon content %	Hydrogen content %	CO_2 emission Kg/MWh
Coal	> 90	5-6	900
Petroluem crude	84 - 88	10-13	565
Natural gas	75 -77	20-25	365
Hydrogen	0	100	0

Source: Kotak Institutional Equities

Below are few other key properties of H_2:

- At normal temperature and pressure, H_2 is a colorless, odorless and tasteless gas. This makes H_2 leaks difficult to detect with human senses.
- The low weight and small size of H_2 leads to high diffusivity. H_2 can leak through fittings, flanges, threads, gaskets, porous materials and others. As H_2 diffuses quickly in an open environment, its leakage is relatively safe in an open environment.
- H_2's auto-ignition temperature of 585°C is higher versus most hydrocarbons. However, it has a wide range of flammability of 4-77% in air. It also requires much lower ignition energy of below 0.02 MJ, which is an order of magnitude lower than other hydrocarbons (1/15th of methane). This means that proper care is needed to ensure that ignition sources are eliminated from the vicinity of H_2.
- Though H_2 is non-corrosive and non-reactive at normal temperatures, it is capable of reducing the mechanical strength of some material (including some steel pipelines) by a process called H_2 embrittlement.

Exhibit 58: H_2's physical properties

	unit	value	comments
Physical properties			
Density (gaseous)	kg/m3	0.089	at 0 deg C, 1 bar
Density (liquid)	kg/m3	70.8	at -253 deg C, 1 bar
Boiling point	deg C	-253	90 deg C below LNG
Energy content			
Specific energy HHV	MJ/kg	142	3x of gasoline
	kWh/kg	39.4	3.3x of diesel
Specific energy LHV	MJ/kg	120	2.5 x of LNG
	kWh/kg	33.3	
Ignition properties			
Flame velocity	cm/s	346	8x of methane
Ignition range in air	%	4 -77	6x wider than methane
Autoignition temperature	deg C	585	220 deg C for gasoline
Ignition energy	MJ	0.02	1/15 of methane

Source: Kotak Institutional Equities

A2

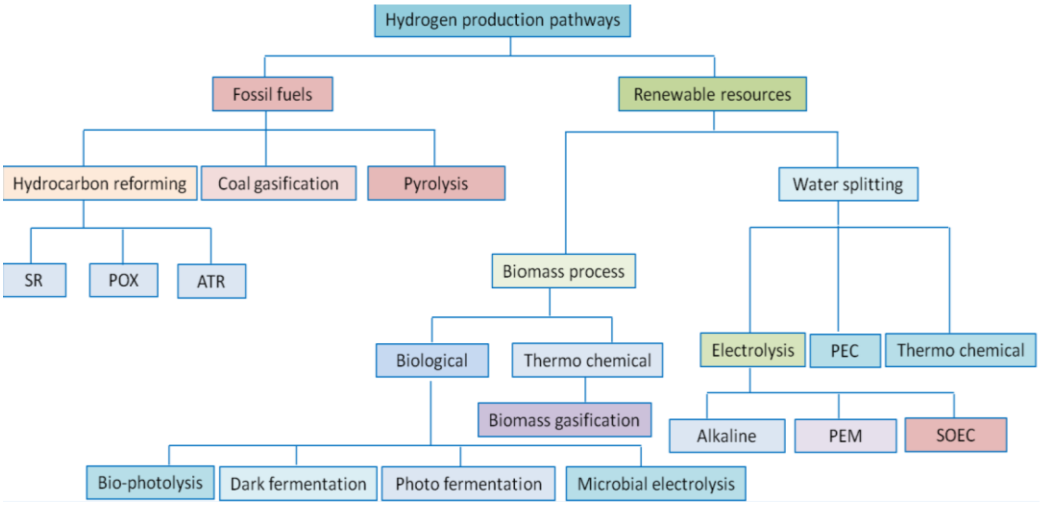
Annexures 2: Multiple colors, yet one product

As we highlighted earlier, H_2 is a colorless, odorless and tasteless gas. However, H_2 is classified in different color codes based on its production/extraction process. There are multiple pathways to produce H_2 using fossil fuels and renewable resources such as bio-mass or water electrolysis using renewable energy.

Exhibit 59 illustrates the different production pathways using fossil fuels and renewable resources. Using fossil fuels, most H_2 is produced using steam reforming. There are other methods as well such as partial oxidation (POX), auto thermal reforming (ATR), coal gasification and pyrolysis. For water splitting using renewable energy, electrolysis is the primary method. There are several new pathways currently under the research phase such as photo-electro-chemical (PEC) and thermochemical water splitting.

Most H_2 produced using steam reforming currently; electrolysis using renewable to emerge as key source

Exhibit 59: Various pathways for H_2 production



Source: Ministry of New and Renewable Energy, Kotak Institutional Equities

Exhibit 60 illustrates key color codes based on the process to produce H_2. With new processes emerging, more color codes are likely to be added to this list.

Gray H_2

This is the most prevalent method to produce H_2 currently. H_2 is produced from fossil fuels (typically natural gas), using the steam methane reforming (SMR) process. This process leads to large emissions of CO_2 in the atmosphere.

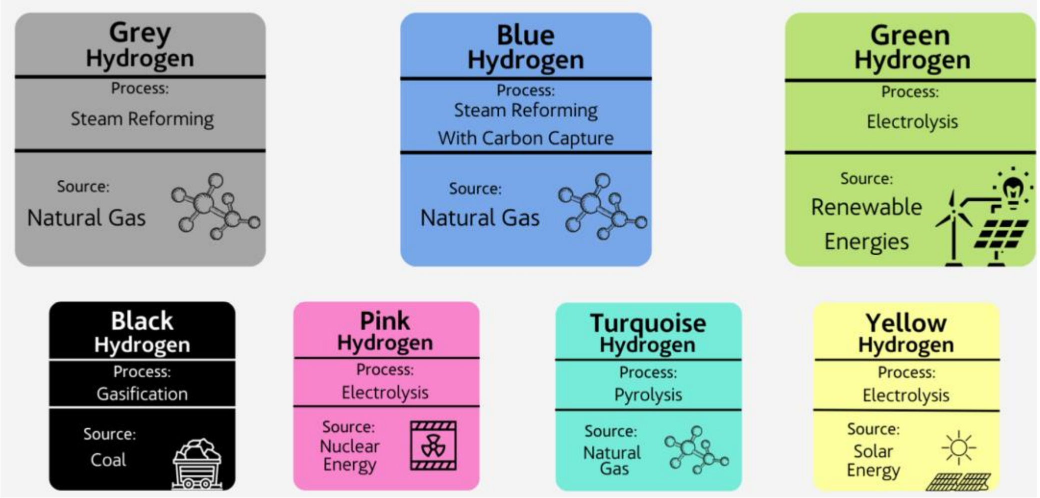
In the SMR process, methane reacts with steam at a high temperature of 700-1,000°C and 3-25 bar pressure in the presence of a catalyst. The process, apart from H_2, produced carbon monoxide (CO) and a small amount of CO_2. CO further reacts with steam in a "water-gas" shift reaction to produce more H_2, in a subsequent process.

Steam-methane reforming: $CH_4 + H_2O$ (+ heat) $\rightarrow CO + 3H_2$

Water-gas shift reaction: $CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

For each ton of H_2 production, this process produces about 10-12 ton of CO_2. According to IEA, nearly 6% of global gas production is utilized to produce H_2. The usage of fossil fuels (including coal) in producing gray H_2 results in nearly 800 mn ton of CO_2 emissions annually.

Exhibit 60: H_2 color codes based on method of production



Source: Acciona Energia; Kotak Institutional Equities

Blue H_2

Blue H_2 is also produced using fossil fuels through the steam reforming process. However, the effort is to decarbonize the process by capturing carbon emissions and utilizing or storing these emissions. This additional process is called carbon capture utilization and storage (CCUS).

In the CCUS technology, exhaust gas from the SMR process is passed through a solvent that captures CO_2. Later, as the solvent is heated, CO_2 bubbles out and can be captured. The captured CO_2 can either be used at site, transported elsewhere or injected in deep reservoirs or saline aquifers.

CCUS can be retrofitted to plants and can tackle emissions in hard-to-abate sectors such as cement, steel, refineries, fertilizers and chemical plants. The adoption of CCUS by existing plants may be the most cost-efficient method to reduce emissions.

However, one key drawback of CCUS is that the **process is not fully efficient and 10% or more CO_2 gets leaked out to the atmosphere.** Thus, the process is not completely zero emission.

The CCUS technology has also been criticized by climate researchers and environmental advocacy groups. The reasons include: 1) Despite the existence of the technology for several decades and significant subsidies, investments in CCUS have not scaled up, 2) the CCS technology, itself, needs energy to run and thus, the entire process requires more fossil fuel consumption, 3) large quantities of captured CO_2 create an issue in handling this; unproven storage can lead to CO_2 itself leaking out and causing water contamination or air pollution again and 4) CCS competes with renewable fuel technology. Investment required in CCS may be much less than switching completely to a renewable technology. There are concerns that CCS may just be used as a greenwash. Few industries may continue to use fossil fuels and continue to pollute the environment.

GH

H_2 produced by the electrolysis of water using only renewable energy is termed GH. It is termed GH, as in this process there are no CO_2 emissions either in production or its usage. Apart from electrolysis, H_2 produced by renewable sources as biogas is also termed GH or even deep GH.

Electrolysis is a process of using electricity to break the chemical bond of H_2 and oxygen. The reaction takes place in a unit called electrolyzer. The electrolyzer consists of an anode and a cathode separated by an electrolyte. During the process, pure H_2 is formed and released at the cathode, while oxygen releases at the anode. **About 9 liters of de-mineralized water is needed to produce 1 kg of H_2 and 8 kg of oxygen.** The efficiency of current electrolyzers ranges 50-75%.

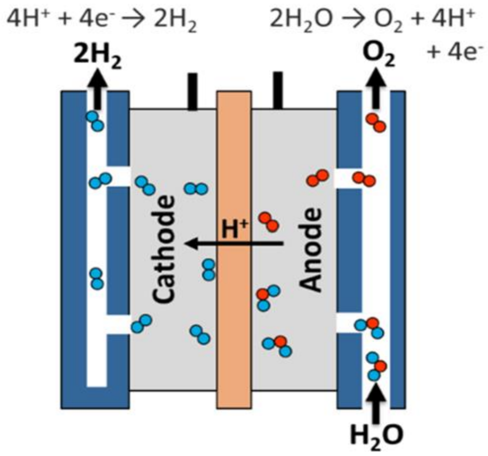
GH has generally been more expensive than blue H_2. However, with falling prices of renewable energy, its cost-competitiveness is rising. In several countries, including India, with renewable energy prices low, GH prices are likely to get lower versus both gray and blue H_2.

There are **several types of electrolyzers** that are in different stages of development.

Alkaline and **proton exchange membrane (PEM)** electrolyzers are commercially available. The alkaline electrolyzer is a more mature technology, with a history of deployment in the chloralkali industry. However, both technologies are not competitive, with current fossil fuel-based H_2 production without CCS (gray H_2).

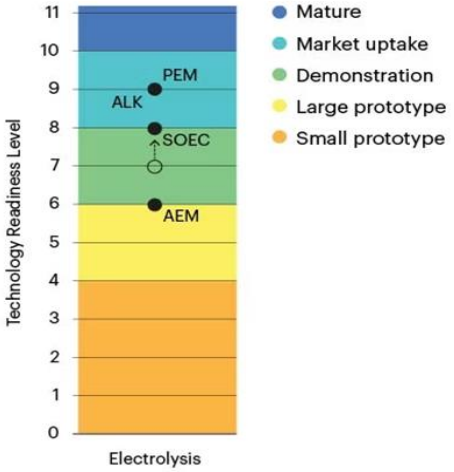
Solid state electrolyzer cells (SOEC) are quickly approaching commercialization stage. **Anion exchange membrane (AEM)** electrolyzers are at a prototype level.

Exhibit 61: Basic electrolysis process



Source: Energy.gov, Kotak Institutional Equities

Exhibit 62: Technology readiness of electrolyzer technologies



Source: Energy.gov, Kotak Institutional Equities

Black or brown H_2

Black or brown H_2 is created if produced from coal (black) or lignite (brown). H_2 production is using the process called gasification and if CO_2 is released in air, it is even more polluting than gray H_2 production.

Pink

Similar to GH, pink H_2 is produced through the electrolysis of water. However, rather than renewable energy, it is powered by nuclear energy.

Turquoise

Turquoise H_2 is produced using **pyrolysis of fossil fuels such as methane**. In this process, heat is used to break down methane into carbon and H_2. The process releases solid carbon, which can be collected and stored.

Turquoise H_2 is very new and is still in the process of evaluation—if it can be used well on a large scale. It is made using a process called 'methane pyrolysis', which produces H_2 and solid carbon by using heat to break down a material's chemical makeup. No carbon is released into the air, instead it is stored in the solid carbon created. If proven to be effective, turquoise may join blue as a 'low-carbon hydrogen', if the carbon can be permanently stored in an environmentally safe manner.

Yellow

Yellow H_2 is essentially **GH specifically made using solar power only**. It has a more specific color to clarify which form of renewable energy has been used to produce it.

Although there are multiple colors assigned to H_2, the end-product is the same, i.e., H_2. In comparison, for crude oil, each reservoir is different and produces different grades. Grades have different chemical compositions, different density (light or heavy), different sulfur content (light or heavy) or different pH levels (acidic) and others. This requires each crude to be refined differently and could produce varying proportion of end-fuels such as diesel, gasoline, naphtha and fuel oil, which are used in various applications and marketed/transported separately.

In contrast, H_2 will be one single fuel, which can be used in a variety of applications. This will make H_2 trading relatively easier versus oil/product markets.

A3

Annexures 3: Electrolyzer costs likely to see sharp declines

As we noted above, apart from lower renewable energy prices, the key driver of H_2 cost reduction would be electrolyzers.

Water electrolyzers can be divided into three key parts: **1) Cell**—it is the core of electrolyzers, where the key electrochemical reaction to split water into hydrogen and oxygen happens, **2) stack**—consists of multiple cells connected in series, spacer, seals, frames and end plates and **3) balance plant**—includes power supply, water supply and purification, H_2 compression and processing. Exhibit 63 shows the basic components of electrolyzers.

The general principle for electrolysis has remained the same since it was first developed in the 18th century. At the electrode, purified water is split into oxygen and hydrogen and ions (H^+ and OH^-) travel through the electrolyte (solid or liquid). The membrane or separator between electrodes also keeps produced gases (H_2 and oxygen) separate.

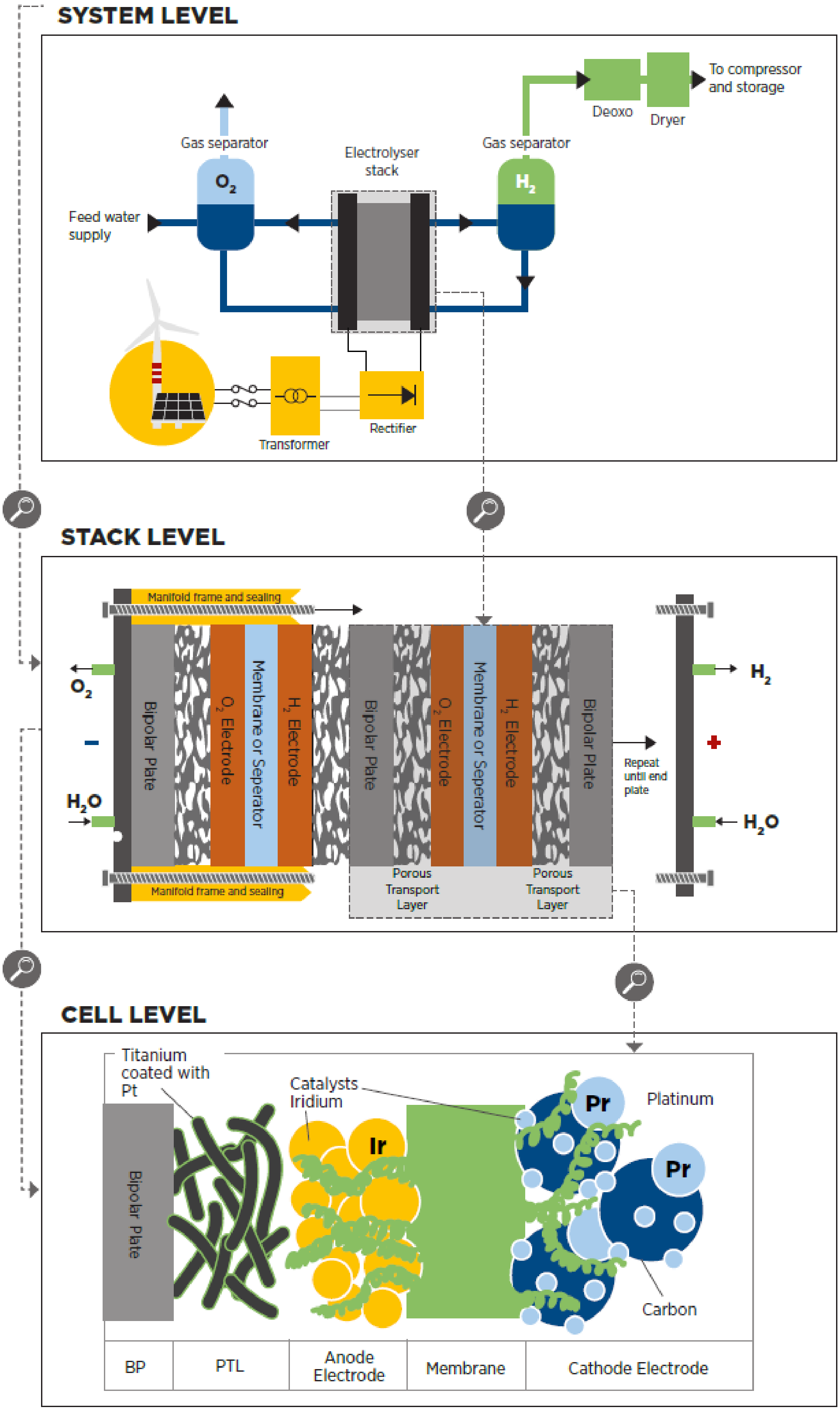
As we noted earlier, there are four types of electrolyzers. Alkaline and polymer electrolyte membrane (PEM) electrolyzers are already commercial. Anion exchange membrane (AEM) and solid oxide electrolyzers are currently at lab-scale, but look promising. Exhibit 64 gives the key components and operating conditions of different types of electrolyzers.

Each technology at this stage has its own advantages and challenges; there are no clear winners at this stage. With further research and deployment, all these technologies are likely to see improvement in efficiency, reliability and cost reductions. Even though both alkaline and PEM technologies are relatively mature, these are still more expensive compared with fossil fuel-based H_2 production on capex and opex.

IRENA expects that with innovations and mass deployment of electrolyzers, the gaps in cost and performance of all technologies will decline and converge to similar levels in terms of key performance indicators and costs.

Exhibit 65 shows the comparison of key performance indicators of electrolyzer technologies and how these could improve by 2050, according to IRENA's forecasts.

Exhibit 63: Basic component of water electrolyzers at cell, stack and system levels



Source: IRENA—green hydrogen cost reduction; Kotak Institutional Equities

Key features of different types of electrolyzers

Exhibit 64: Key components and operating features of electrolyzers

	Alkaline	PEM	AEM	Solid Oxide
Operating temperature	70-90 °C	50-80 °C	40-60 °C	**700-850 °C**
Operating pressure	1-30 bar	< 70 bar	< 35 bar	1 bar
Electrolyte	Potassium hydroxide (KOH)	PFSA membranes	DVB polymer with KOH or NaHCO3	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO2 stabilized with PPS mesh	Solid electrolyte	Solid electrolyte	Solid electrolyte
Electrode / catalyst (oxygen side)	Nickel coated perforated SS	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type
Electrode / catalyst (hydrogen side)	Nickel coated perforated SS	Platinum nano-particles on carbon black	High surface area nickel	Ni/ YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon Cloth	None
Bipolar plate anode	Nickel-coated SS	Platinum-coated titanium	Nickel-coated SS	None
Bipolar plate cathode	Nickel-coated SS	Gold-coated titanium	Nickel-coated SS	Cobalt-coated SS
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

Notes:

PFSA = Per-fluoro-acid-sulfonic; PTFE = Poly-tetra-fluoro-ethylene; ETFE = Ethylene Tetra-fluor-ethylene; PSF = poly (bisphenol-A sulfone); PSU = Poly-sulfone; YSZ = yttria-stabilized zirconia; DVB = divinyl-benzene; PPS = Poly-phenylene sulphide; SS = stainless steel.

Source: IRENA—green hydrogen cost reduction; Kotak Institutional Equities

Significant costs improvement likely in all types of electrolyzers; no clear winner at this stage

Exhibit 65: Electrolyzer technologies KPIs in 2020 and likely in 2050

		2020				2050			
		Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Efficiency	kWh/Kg H_2	50-78	50-83	57-69	45-55	< 45	< 45	< 45	< 40
Lifetime	000 hours	60	50-80	> 5	< 20	100	100-120	100	80
Capital cost range									
- for stacks	US$/kW	270	400		> 2 000	< 100	< 100	< 100	< 200
- entire system	US$/kW	500 -1000	700 -1400			< 200	< 200	< 200	< 300

Note

(a) PEM = Polymer Electrolyte Membrane;

(b) AEM = Anion Exchange Membrane; SOEC = Solid Oxide Electrolyzers (both at lab-scale currently)

Source: IRENA—green hydrogen cost reduction; Kotak Institutional Equities

A4

Annexures 4: Transportation and storage of H_2 is challenging

As we noted earlier, being the lightest molecule, H_2 has a low energy density at atmospheric pressure, which makes it difficult to transport and store H_2. On the other hand, transportation over a long distance and storage of fossil fuels are relatively easier.

Currently, majority of H_2 usage is captive, with production and consumption on the same site (such as in ammonia production and refining), with a very small amount of H_2 requiring transportation and storage. Transportation and storage of H_2 are critical for the commercial uptake of H_2 for various applications such as stationary power, portable power and mobility. The cost of transportation and storage of H_2 would also play a significant role in the overall delivered cost of H_2.

Transportation of H_2

Depending on distance, volume and the state (gas or liquid), H_2 can be transported in three main ways, i.e., pipelines, rail, road and tanker ships. Storage medium for transport includes compressed H_2, liquid H_2 or converted H_2 (to ammonia or methanol) and absorbed H_2 (such as metal hydrides).

As current volumes are low, the most common method to transport is compressed H_2 (200 to 500 bar) through road. H_2 transit through rail is less common, unless it is converted to ammonia. Only few areas have dedicated H_2 pipelines over short distances to meet refining and pipeline needs.

As H_2 usage increases, pipelines are likely to be the most cost-effective long-term choice for H_2 distribution.

For overseas shipping, H_2 is either liquefied and shipped in dedicated liquid H_2 ships or it could be transported as liquid ammonia or as liquid organic hydrogen carriers (LHOCs).

Storage of H_2

In order to be used as a feedstock for industrial processes, H_2 storage would be required. H_2 can be stored as a gas (in pressurized form) or converted into liquid form at cryogenic temperatures ((-)253^{o}C) or as an absorbed medium. The choice of storage medium depends on the 1) volume to be stored, 2) duration of storage, 3) required speed of discharge and 4) geographical availability of storage options.

For small-scale storage over a short term, H_2 can be stored in tanks, whereas for large-scale storage over a long term, geological storage such as salt/rock caverns may be a better option.

Storage tanks: The most common form of H_2 storage is a high-pressure steel tank, where H_2 can be stored in compressed and cryo-compressed form. Storage tanks have a high discharge rate and efficiencies, which makes them an appropriate storage method for small-scale applications. As compressed H_2 has a low energy density (~15% of gasoline), storing H_2 would require significantly more space and make storage tanks one of the most expensive storage methods and restrict the use of steel tanks as a storage method for large-scale applications.

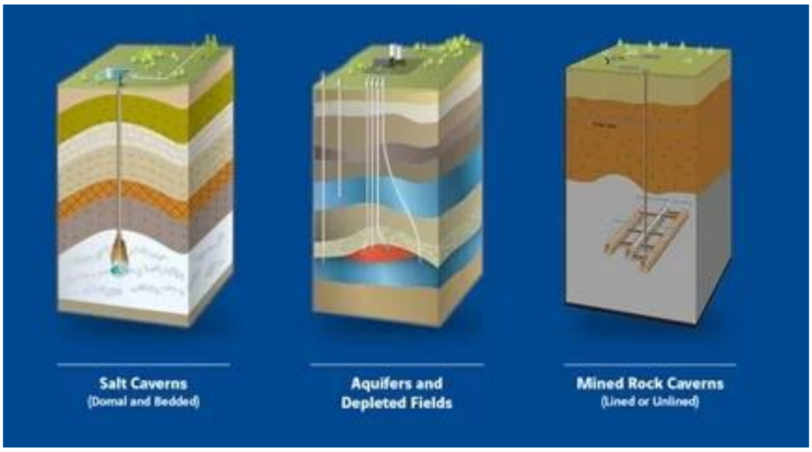
Chemical storage: As H_2 has low energy density, another storage option could be to convert H_2 to compounds such as liquified organic hydrogen carriers (LOHCs), for instance, methanol and toluene, or as hydrides such as ammonia. These compounds have greater energy density and would reduce the need for storage space, but conversion to these compounds and reconversion to H_2 would entail additional costs.

Geological storage: Geological storage such as salt caverns, depleted natural gas and oil reservoirs, and aquifers is a possible option for large-scale and long-term H_2 storage. Geological storage provides significant economies of scale and high efficiency, which would likely lead to lower storage costs. Geological storage is already being used for natural gas/crude oil storage in several countries. However, local availability of geological storage near H_2 production plants could be a key challenge.

Exhibit 66: Liquid H_2 storage tank at NASA's Kennedy Space Center

Source: NASA, Kotak Institutional Equities

Exhibit 67: Underground storage options for H_2 storage



Source: www.entrepose.com, Kotak Institutional Equities

H_2 storage in vehicles a bigger challenge

Though H_2 has one of the highest specific energies (energy per kg of weight), its low density and low temperature make it a difficult fuel to handle. It either needs to be kept at high compression or at cryogenic temperature. New methods such as storing as metal hydrides or absorbing in carbon nano-materials are emerging.

Compressed storage has least energy density, but is relatively a mature technology

Exhibit 68: Different type of storage options for H_2

		Compressed H_2	Liquid H_2	Metal Hydrides	Carbon Nanomaterials
Energy density					
(kWh/kg)		1.6- 1.8	2.0	1 – 4.6	3.6
KWh/liter		0.66 - 0.75	1.2		
Advantages		Easy to de-/refuel	Higher energy density versus pressure storage	High energy density at high operating temperatures	Very high energy density at room temperature
		Relatively mature technology			Do not absorb H_2
Disadvantatges		High operating pressure of 350 or 700 bars	Low cryogenic temperature of -253 degree C	Heat needed to release hydrogen	High density limited to low number of charging cycles
		Limited energy density	Boil-off of 0.3-3% daily	Anisotropic expansion as H_2 diffuses in metal and causes material fatigue	Technology at early stage

Source: www.mdip.com; Kotak Institutional Equities

Compressed storage

Compressed H_2 storage is one of the most established and mature technologies. There are four types of storage vessels:

- **Type I** is made of steel and is the heaviest. It is used only for stationary application.
- **Type II** is a metal line hoop-wrapped composite cylinder that weighs less than Type I. However, this is also unsuitable for vehicle storage.
- **Type III** vessels comprise a fully wrapped composite cylinder, with a metal line made of aluminum alloy. The composite overwrap (usually carbon fiber) acts fully as the load-bearing component. Type III vessels are 25-30% lighter versus Type I/II.
- **Type IV** vessels comprise a fully wrapped composite cylinder, with an HDPE liner, which acts as a barrier to H_2 permeation.

Due to their ability to handle higher pressure and relatively lower weight, **type III and type IV cylinders are preferred for vehicles**. Typical pressures used are 350 bar or 700 bar. Compared with the amount of fuel stored, the cylinder weight will be much higher. A 30-liter tank would store just 1.2 kg of H_2 and weigh about 26 kg; it would carry only about 1.6 kWh/kg of energy. For a 120-liter tank, carrying about 5 kg of H_2, energy density will improve to 1.8 kWh/kg.

Liquid H_2

H_2 can also be kept in liquid form at a temperature of negative 253°C (20 K). The density in liquid form (70.8 kg/cubic meter) is higher than compressed H_2 at 700 bar (39 kg/cubic meter). This can lead to improved energy density for vehicles (2 kWh/kg or 1.2 kWh/liter).

However, using liquid H_2 for vehicles is a challenge. Liquefaction itself is energy-intensive. Maintaining low cryogenic temperature in a vehicle is difficult. Despite super-insulated vessels with high vacuum separation, boil-off losses can be 0.3 to 3% daily. Thus, this method is not suitable for vehicle transport.

Material-based H_2 storage

In these methods, H_2 either gets absorbed chemically or gets adsorbed on the surface of various materials. The advantage of this method of storage as against compressed storage is the operating conditions are quite moderate.

Metal hydrides: Several elements react with H_2 to make metal hydrides. The adsorption process is an exothermic process. In the reverse of the process, H_2 can be released at higher temperatures (and low temperature). Several metals can absorb H_2 up to 3-8% of their weights. This can lead to overall energy density of up to 4.6 kWh/kg, which is higher than liquid H_2-based storage. However, the need to have a high temperature is a key drawback and limits the consideration of this technology for vehicular storage. H_2 can also diffuse into the material, leading to brittleness and cracking.

Carbon nano-materials: Unlike metal hydride, carbon nano-materials do not absorb H_2, but store most part on its surface. Carbon nano-materials have few advantages over metal hydrides. One such advantage is that there is not much expansion during fuel refueling. This can enable a higher charging cycle. This technology, though promising, is still at the early stage of development.

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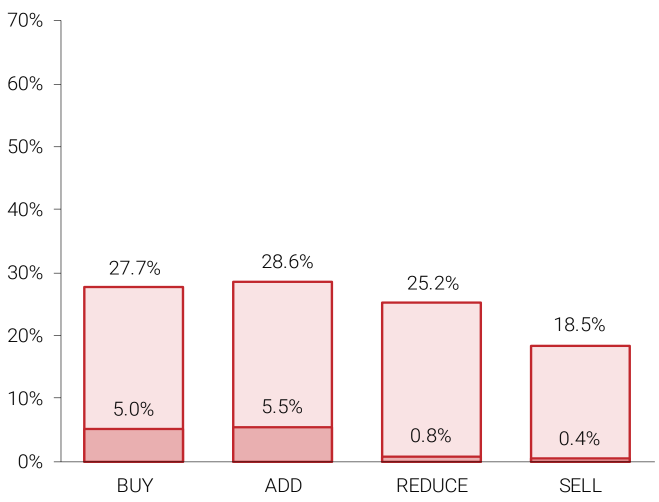

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Source: Kotak Institutional Equities

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